Estimation of The Effect of Rain and Incidents on Freeway Capacity and Free-Flow Speed

By

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Abstract

The goal of this thesis was to examine the effect of incidents and adverse weather (rain) on capacity and Free-Flow Speed (FFS). Data were collected from multiple freeway segments in Kansas City, Kansas from 2014 to 2018. In this thesis, capacities and free-flow speed were measured during four conditions: (1) base conditions, (2) adverse weather only, (3) incidents only, and (4) adverse weather and incidents.

Freeway flow breakdown was assumed to occur when speed dropped below 75% of the Free-Flow Speed. This definition was used for measuring capacity during non-incident conditions. Average discharge flow, i.e., the flow after the breakdown and during congested conditions with duration of at least 15 minutes, was used to identify capacity under incidents conditions.

Capacity Adjustment Factors (CAF), and Speed Adjustment Factors (SAF) were established in this thesis to identify the remaining capacity or the Free-Flow Speed reduction during an incident or adverse weather conditions. CAFs were found by comparing the average capacity during base conditions to the average capacity during adverse weather (rain), incidents, or adverse weather and incidents. Likewise, SAFs were estimated by comparing average FFS during base conditions and average FFS during rain, incident, or rain and incidents. CAFs and SAFs were primarily developed for use within the 6th edition of Highway Capacity Manual (HCM6); although the manual does not provide SAFs for incidents. Also, the effect of incidents along with rain on capacity and FFS is assumed to be additive in the HCM6, but this assumption has not been validated with actual data.

The results from this thesis indicated that rain has minimal effect on capacity. Also, only FFS on three-lanes freeways was impacted by rain. It was also found that incidents and incidents during rain had an impact on capacity and FFS. The measurement location with respect to the closure

during incidents was considered in this research. However, according to the statistical analysis, the location was found to be significant only for incidents during rainy conditions, and only at freeways with two and three lanes.

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1. INTRODUCTION

1.1. Problem Statement

The Highway Capacity Manual, 6th edition (HCM6) estimates a variety of adjustment factors as a function of incidents and adverse weather conditions (1). Capacity Adjustment Factors (CAF), and Speed Adjustment Factors (SAF) can be implemented for a facility to identify the remaining capacity or the free flow speed reduction during an incident or unfavorable weather condition. HCM6 assumes that incidents and adverse weather have an additive effect on capacity; however, this has not been validated through actual data. Also, the manual does not provide SAFs for incidents. As such, this thesis assessed the impact of incidents and adverse weather (rain) on capacity and free flow speed, by analyzing data from multiple freeways in Kansas City, and then compared them to the adjustment factors available in the HCM6 (chapter 11).

1.2. Objective

The objective of this thesis was to estimate the effect of rain and incidents on urbanized freeways' capacity and free flow speed and develop adjustment factors. This thesis also aimed at comparing the developed adjustment factors with those presented in the HCM6.

2. LITERATURE REVIEW

The literature for this study was limited due to the novelty of this research, yet this chapter presents a brief literature review and recent findings related to this thesis topic. First, critical parameters that affect freeway capacity are described. After that, a summary of research on the impact of rainfall on roadway capacity and free-flow speed is presented.

2.1. Effect of Incidents on Capacity and FFS

While conceding the “Maximum Hourly Rate” as the capacity, Smith et al. (3) performed on analysis on demonstrating freeway capacity reduction caused by incidents. The effect of lane blockage on freeways with three lanes was considered for the study. Also, Smith et al. (3) estimated accident capacity as the minimum 10-minutes flow rate recorded in the bottleneck location caused by an incident. It was found that incidents dramatically reduced the remaining capacity on the sturdy locations. A 37% mean capacity was remaining when an incident blocked one out of three freeway lanes. Likewise, an incident with two closure out of three freeway lanes reduced the mean capacity by 77%.

Chin et al. (4) studied the reduction of capacity due to temporary events such as crashes or weather. The study focused on all urban and rural freeways in the nation’s highway system. The total number of open lanes and the number of lanes affected can identify the capacity reductions caused by incidents. Table (1) shows reduced capacity due to freeways incidents. For instance, an incident resulting in the closure of one lane on two-lanes freeways segment reduced the total capacity by 32%.

Table 1 Freeway Capacity Reductions under Incident Conditions (3)

	Lanes Blocked			
Number of Lanes	Shoulder	1-Lane	2-Lanes	3-Lanes
2	0.75	0.32	0.00	N/A
3	0.84	0.53	0.22	0.00
4	0.89	0.56	0.34	0.15*
5	0.93*	0.75	0.50	0.20*

*Assumed

Lu and Elefteriadou (5) estimated the capacity of freeways before and during incident events, and developed a model to evaluate capacity reduction due to incidents. They analyzed data obtained from five locations across North America. Traffic data that include freeway volumes, lane occupancy, and speed, were obtained from the Departments of Transportation (DOTs) archive, in 20- or 30-second intervals. The National Weather Service was used to collect weather records. Finally, incident data were acquired from the states' Highway Patrol agencies or the DOTs. To estimate the capacity, Lu and Elefteriadou defined the breakdown as the speed drops of 10 mi/h for at least 15 minutes.

Four capacity parameters were used in their research, specifically, breakdown flow, maximum pre-breakdown flow, average flow-rate for 10-minutes before breakdown, and average discharge flow. They estimated the available capacity after the incident and compare it with the HCM values. They also developed a regression model for total capacity reduction as a function of the time of incident and the type of lane closure (5).

The impact of incident on capacity and FFS was also evaluated by Kondyli et al. (6) on freeways with narrow lanes. Their analysis indicated that the FFS drop was not statistically significant. On the other hand, Kondyli et al. (6) observed a 22% drop in capacity of in case of an incident or adverse weather, which was found to be statistically significant on twelve out of fourteen sites with the narrow lane segments.

HCM6 (1) provides default CAF values as a function of incidents. Table 2 shows the remaining capacity per open lane related to incident severity. For example, a six-lane directional facility might lose 25% of its original capacity when a two-lane closure scenario occurs, thus, the segment can handle only 75% of the available four open lanes' capacities. However, no information related to SAFs during incident conditions was found in the HCM6.

Table 2 Capacity Adjustment Factors (CAF) as function of Incidents (1)

Directional lanes	No Incident	Shoulder Closed	1 Lane Closed	2 Lane Closed	3 Lane Closed	4 Lane Closed
2	1.00	0.81	0.70	N/A	N/A	N/A
3	1.00	0.83	0.74	0.51	N/A	N/A
4	1.00	0.85	0.77	0.50	0.52	N/A
5	1.00	0.87	0.81	0.67	0.50	0.50
6	1.00	0.89	0.85	0.75	0.52	0.52
7	1.00	0.91	0.88	0.80	0.63	0.63
8	1.00	0.93	0.89	0.84	0.66	0.66

2.2. Effect of Weather on Capacity and FFS

Rakha et al. (7) conducted a study to quantify the effect of inclement weather on the behavior of the traffic stream. Traffic data including free-flow speed, speed at capacity, and jam density, as well as the weather data including precipitation and visibility, were observed in their study. Rakha et al. established adjustment factors for the following parameters: free-flow speed, speed at capacity, and capacity. The base condition was considered to be the no-precipitation condition with visibility of more than or equal to 3 miles. Data were collected at three major cities in the United States: Twin Cities, Minnesota; Seattle, Washington; and Baltimore, Maryland.

Moreover, data were obtained using loop detectors and microwave radar detectors for two years (2002-2004). The weather data were obtained from the Road Weather Information System

(RWIS), and stations located at airports and operated by the National Weather Service. The analysis indicated that the weather conditions had no discernible impact on the traffic jam density. However, FFS, speed at capacity, and Capacity were reduced when light rain (intensity of 0.004 in/hr) occurred for the ranges from 2% to 3.6%, 8% to 10%, and 10% to 11%, respectively. Generally, the increase in the rain amount would increase the reduction in FFS and speed at capacity. The study recorded a maximum decrease of FFS and speed at capacity as 6% to 9%, and 8% to 14%, respectively, depending on the rain intensity. Furthermore, the authors found that the roadway capacity remained steady and the reductions were approximately 10% to 11%, depending on rain intensity range of 0 to 0.67 in/hr.

In contrast to FFS and speed at capacity, increased rain intensity between 0 and 0.67 in/hr did not affect the roadway capacity. Finally, the authors developed multiple adjustment factors as a function of rain intensity (Figure 1). As it can be seen in Figure 1, capacity differences between the weather adjustment factors in the three cities were not statistically significant. However, the differences between the free-flow speed and speed at capacity weather adjustment factors in the three cities were found to be statistically significant (7).

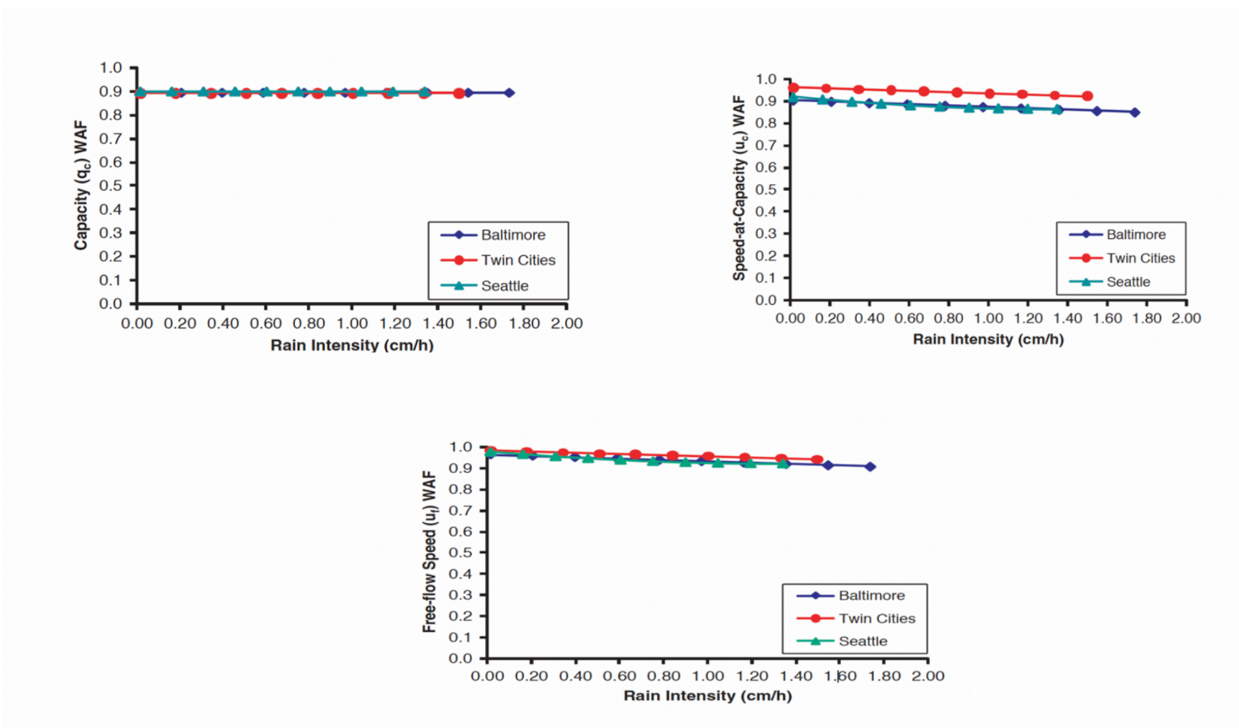

Figure 1 Weather Adjustment Factors as a Function of Rain Intensity, Rakha et al. (7).

The HCM6 provides default CAFs and SAFs as a function of weather type. Table 3 and Table 4 show CAFs and SAFs for medium and heavy rain, and the speed values in the table represent facility FFS. For example, a segment can maintain 92% of the actual capacity when medium rain occurs. Also, as shown in Table 3, a given FFS (e.g., 65mi/h) might drop by a certain percentage (e.g., 6%) during medium rain condition. In addition, CAFs, as well as SAFs, are applied to the base capacity and FFS, respectively (1).

Table 3 CAFs as function of weather (1)

		Capacity Adjustment Factors (CAF)				
Weather Type	**Intensity range**	**55mi/h**	**60mi/h**	**65mi/h**	**70mi/h**	**75mi/h**
Medium Rain	>0.1—0.25 in/h	0.94	0.93	0.92	0.91	0.90
Heavy Rain	>0.25 in/h	0.89	0.88	0.86	0.84	0.82
Light snow	>0.00 – 0.05 in/h	0.97	0.96	0.96	0.95	0.95
Light–medium snow	>0.05 – 0.10 in/h	0.95	0.94	0.92	0.90	0.88
Medium–heavy snow	>0.10 – 0.50 in/h	0.93	0.91	0.90	0.88	0.87
Heavy snow	>0.50 in/h	0.80	0.78	0.76	0.74	0.72
Severe cold	<-4°F	0.93	0.92	0.92	0.91	0.90
Low visibility	0.50 – 0.99 mi	0.90	0.90	0.90	0.90	0.90
Very low visibility	0.25 – 0.49 mi	0.88	0.88	0.88	0.88	0.88
Minimal visibility	< 0.25 mi	0.90	0.90	0.90	0.90	0.90
Non–severe weather	All conditions not listed above	1.00	1.00	1.00	1.00	1.00

Table 4 SAFs as function of weather (1)

		Speed Adjustment Factors (SAF)				
Weather Type	**Intensity range**	**55mi/h**	**60mi/h**	**65mi/h**	**70mi/h**	**75mi/h**
Medium Rain	>0.1—0.25 in/h	0.96	0.95	0.94	0.93	0.93
Heavy Rain	>0.25 in/h	0.94	0.93	0.93	0.92	0.91
Light snow	>0.00 – 0.05 in/h	0.94	0.92	0.89	0.87	0.84
Light–medium snow	>0.05 – 0.10 in/h	0.92	0.90	0.88	0.86	0.83
Medium–heavy snow	>0.10 – 0.50 in/h	0.90	0.88	0.86	0.84	0.82
Heavy snow	>0.50 in/h	0.88	0.86	0.85	0.83	0.81
Severe cold	<-4°F	0.95	0.95	0.94	0.93	0.92
Low visibility	0.50 – 0.99 mi	0.96	0.95	0.94	0.94	0.93
Very low visibility	0.25 – 0.49 mi	0.95	0.94	0.93	0.92	0.91
Minimal visibility	< 0.25 mi	0.95	0.94	0.93	0.92	0.91
Non–severe weather	All conditions not listed above	1.00	1.00	1.00	1.00	1.00

Camacho et al. (8) evaluated the effect of inclement weather on FFS by developing several non-linear regression models. The reduction in the FFS caused by different weather conditions such as rain, snow, wind speed, and visibility loss was quantified. Fifteen sites from Northwestern freeways in Spain were chosen for the study, and all of them were two-lane directional facilities. Moreover, the fifteen two-lane freeways were affected by the Atlantic climate, and, thus, were considered as the most cloudy and wettest locations in Spain. The authors stated that the annual rain amount for the selected stations was between 31.5 inches and 59 inches per year, and the average summer temperature was between 48 F° and 64 F°.

Furthermore, weather and traffic data were collected using different measurement stations for the period between January 2006 to November 2008. Taking into account the time interval, the authors used one hour for the traffic data, while the weather stations provided data for 15- minute intervals. However, to make the analysis between the traffic and the weather variables data accurate, they divided the traffic data into four similar 15-minute intervals. Also, the weather variables were split into the following four groups:

1- Normal conditions and temperature above 32 F°.
2- Normal conditions and temperature below 32 F°.
3- Rain.
4- Snow.

It was found that the rainfall had an impact on the FFS between 3.4 mi/hr to 4.3 mi/hr depending on the intensity. Furthermore, snow reduced the FFS dramatically from 5.6 mi/hr to 8.5 mi/hr. As long as the wind speed was greater than 8 m/s, speed was affected. Likewise, no effect was observed on the FFS when the visibility was around 1.2 miles (8).

Jia et al. (9) quantified the effect of different rainfall intensity levels on urbanized facilities in China. Beijing was the main scope of the authors' study due to the abundance of traffic data that have been recorded for years. They collected data on three streets, which had a maximum speed of 50 mi/hr, an average daily traffic of more than 100,000 vehicles, three lanes in each direction, and nearly 100 loop detectors spread over every kilometer on each lane. Moreover, the two-minute interval traffic data included flow rates, mean speeds, and lane occupancies, and these were retrieved from the Beijing Traffic Management Bureau (BTMB).

Furthermore, the hourly rain data were obtained by the National Meteorological Center (NMC). It was found that as the level of the rainfall increased, the capacity of each facility chosen in the study (both directions) decreased (figure 2). The average reduction was found to be 5% to 10% for light rain, 13% to 21% for medium rain, and finally 17% to 25% for heavy rain. Statistically, the difference between the three rainfall categories was examined to determine whether the reductions among them were significant. Using the Bonferroni test with 0.05 significance level, it was discovered that the reductions are meaningful when compared to good weather conditions, whereas no such differences were found between medium and heavy rain as the data points from heavy rain category were insignificant (9).

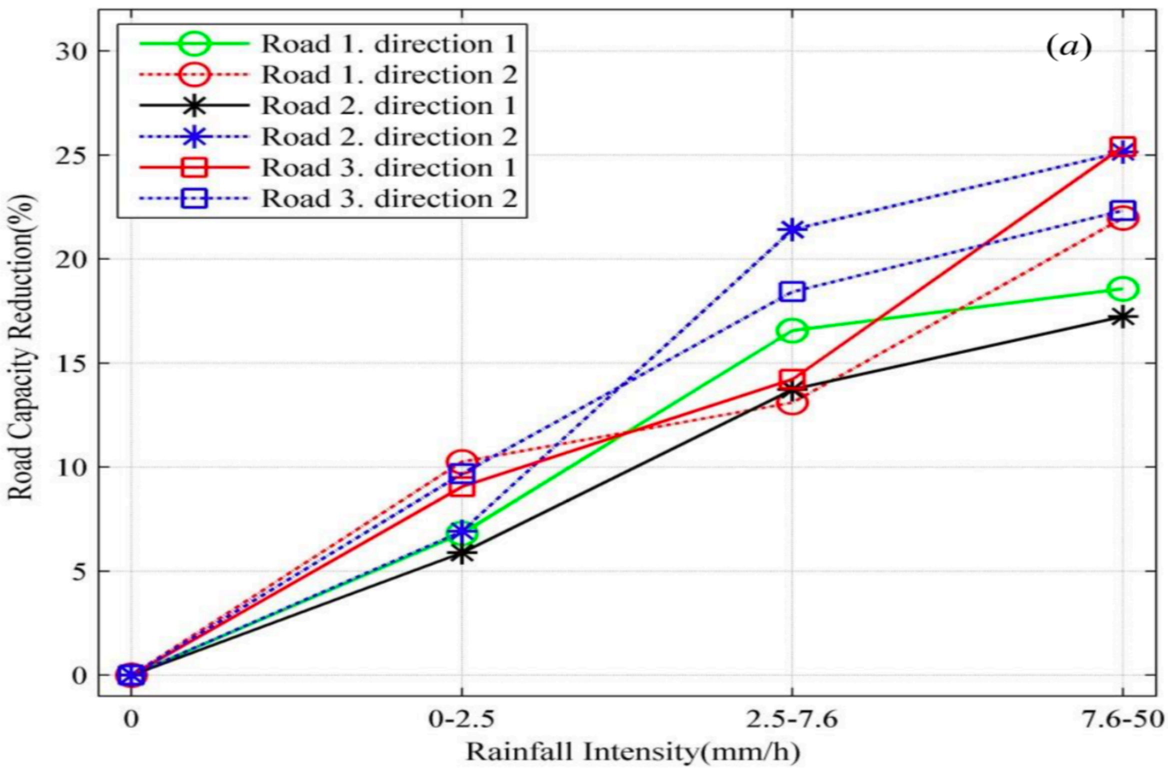

Figure 2 Road capacity reductions for three rainfall conditions. (9)

In 2017, Singh (10) evaluated the impact of rainfall on key traffic parameters, free-flow speed, speed at capacity, and capacity in dry places. The main objective was to examine the effect of rain on traffic parameters in dry locations, and compare it to previous investigations, which were focused more on the wet areas, and then to determine if there were any regional differences between them. Six freeways, I-10, I-5, I-210, I-405, and I-105, in Southern California, were chosen for the study. About 4,550 stations and 10,000 loop detectors provided by Caltrans Performance Measurement System (PeMS), in Los Angeles County collected the traffic data for the study. Also, the data included speed, flow, and lane occupancy that were downloaded in five-minute intervals from 2009 to 2015.

Furthermore, 15-minute precipitation data were retrieved by the Los Angeles Hydrology Department. The author compared the reduction in traffic parameters due to rainfall with two other sources, HCM 2010 (2) and Rakha et al. (10). Figure 3 shows the percent drop in free-flow speed, speed at capacity, and capacity from Rakha et al. (7), HCM 2010, and Singh (10) in multiple cities.

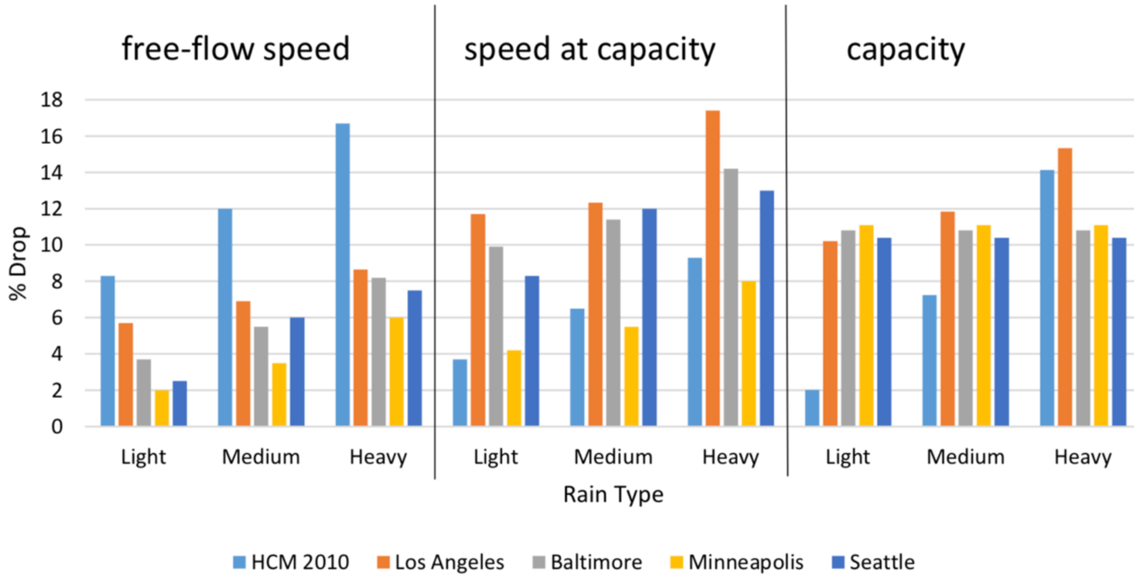

Figure 3 Percent drop in traffic parameters at various cities. Retrieved from Singh. (10).

Generally, the impact of rain on the free-flow speed, the speed at capacity, and the capacity of freeways, and the outcomes were found to be different from the previous recourses in the following ways:

1- Free-flow speed was reduced due to light, medium and heavy rain on an average of 5.7%, 6.91%, and 8.65%, respectively. However, these reductions are less compared to the HCM and Rakha et al. (7).

2- The average drops in the speed at capacity due to different rainfall amounts were found to be higher than HCM 2010 and Rakha et al (7) by 11.71% for light rain, 12.34% for medium rain, and 17.4% for heavy rain.

3- The average capacity was also dropped for light, medium, and heavy rain, by 10.22%, 11.85%, and 17.4%, respectively. These reductions in capacity were found to be more than the results from HCM 2010 (8) for the medium and heavy rain. Nevertheless, for the light rain, the reduction was greater compared to HCM 2010, and somewhat less than Rakha et al. (7). (10).

2.3. Summary

Capacity can be examined under four parameters, breakdown flow, maximum pre-breakdown flow, average flow-rate for 10-minutes before breakdown, and average discharge flow. According to Lu and Elefteriadou (5), the capacity under incident conditions can be estimated using two factors; the average discharge flow per open lane when both an incident and congestion are present, and the minimum 10-minute flow rates during that same period. Finally, in most cases, rain has an impact on capacity and FFS at different intensity levels.

3. METHODOLOGY

This chapter provides an overview of the methodology used to complete the research. First, the definitions of traffic stream parameters that were utilized as part of the analysis are presented. Then, the data collection plan and general procedures are addressed. After that, data collection recourses and the expected data points are discussed.

3.1. Key Traffic Stream Parameters

Based on the literature, the definition of capacity can vary depending on the researcher. Also, the capacity measurement involves different traffic parameters. As a result, this section defined the essential key parameters that helped define capacity and FFS.

3.1.1. Breakdown

The definition of capacity is related to the breakdown event (11). When traffic demand is more than capacity, a sudden drop in speed occurs (i.e., breakdown) (1) (11). Based on the literature ((5), (11)) the identification of a breakdown can be found as the sudden drop of speed by more than 10 mi/h. However, in this research, breakdown was assumed to occur when speed drops below 75% of the FFS, according to the HCM definition (1). This method has been previously practiced by Asgharzadeh and Kondyli (13) and Kondyli et al. (6) and it was further improved by Asgharzadeh and Kondyli (14) by including the speed drop intensity (percentage) as a factor of breakdown.

3.1.2. Free Flow Speed (FFS)

Determining the Free-Flow Speed reduction is one of this thesis objectives. The FFS is also a tool used for capacity identification. Moreover, the Free-Flow Speed can be found at a point when the density is very low (12). In this research, FFS is defined as the average speed of a facility under low flow rate (12), i.e., less than 1,000 veh/hr/ln.

3.1.3. Pre-Breakdown Flow Rate

This is defined as the average 5-minute flow rate right before the speed drops below 75% of the FFS (11).

3.1.4. Average Discharge Flow

This definition was obtained from Elefteriadou (11), and it is the average per lane flow rate after the breakdown event, measure during congested conditions with a duration of at least three 5-minute intervals (15 minutes).

3.1.5. Capacity and FFS Measurements

Capacity definition varies depending on the prevailing conditions. Four types of prevailing conditions were considered in this study, and capacity under each condition is defined below. Also, in this thesis, capacity was not the maximum flow rate. Instead, pre-breakdown flow and discharge flow for non-incidents and incidents events, respectively, were used for capacity description. FFS measurement information is also provided below.

1. **Base Conditions (good weather, no incident)**

   For this type of conditions, congestion occurs due to excess of demand, and not due to an incident. As such, capacity is defined as the pre-breakdown flow rate. FFS was measured at the same locations under low flow conditions.

2. **Incidents and Good Weather**

   During incidents, the average discharge flow was used as the capacity. Average discharge flow was chosen instead of pre-breakdown flow because incidents were assumed to cause the congestion. In those cases where an incident occurred, but the incident was not significant enough to cause congestion, FFS was measured, if the flow was less than 1,000 veh/hr/ln.

3. **Adverse Weather (rain) and No Incidents**
The average pre-breakdown flow rate was assumed to be the capacity, in case of a breakdown. Also, the average speed at the same location when the flow rate was lower than 1,000 veh/hr/ln was the adverse weather FFS, in case on free-flowing conditions.

4. **Adverse Weather (rain) and Incidents**
The average discharge flow was assumed to be the capacity here. Additionally, FFS was defined as the average speed during an incident/adverse weather event that did not lead to congestion.

3.1.6. CAF

According to the HCM 2016, the capacity adjustment factor can be defined as the percent of the capacity remaining after a particular event occurred such as incident or adverse weather (1).

3.1.7. SAF

This is the average speed remaining during particular events such as incident or adverse weather (1).

3.2. Data collection Plan

This section describes the data collection recourses and methods used to obtain traffic, incident, and weather data. Also, this section provides an overview of the procedures used to collect and analyze the data.

Data including traffic and weather were collected for the period from 2014 to 2018 on various freeways in Kansas City. Two-lane, three-lane, and four-lane freeways, in each direction were considered in this study. Additionally, data were obtained using two major data portal websites: KCSCOUT and Weather Underground, WU.

3.2.1. KCSCOUT

Traffic data were collected through KCSCOUT (www.kcscout.com), Kansas City’s bi-state traffic management system. KCSCOUT measures traffic in the Kansas City metropolitan area by using various loop detectors that spread over more than 300 miles of freeways. As part of this source's features, two portals from KCSCOUT were used to collect the traffic and incident data for the study. The two portals are described in the following section.

Event Viewer

Event viewer was the starting point of the research data to locate the historical incidents that took place in Kansas City. KCSCOUT reports any event such as crash or stalled vehicle. The inquiry from this web page can cover an event with numerous details. For example, a major or minor accident or stalled car is categorized as the event type. Also, the report allows the user to identify the location of the event, for example, I-435 WB and Antioch Rd.

Furthermore, the lane pattern can be classified as the following; ML: Middle lane LE: Lane exit/entrance, LS: Left shoulder. The example from Table 5 shows there was a minor accident on I-435 WB at Antioch Rd in July 2016. The segment where the accident occurred had initially three lanes in each direction, and one became blocked due to the incident. By using Google Maps, the longitude and latitude information provides the exact location of the event.

Table 5 Example from the Event Viewer report (retrieved from www.kcscout.com)

Event Type	Road Type	Main Street	Cross Street	Direction	Latitude	Longitude	County	State	Start Time	Event Cleared	Lane Pattern*	Blocked Lanes
minor accident	I	I-435 WB	AT ANTIOCH RD	W	38.934426	-94.682443	Johnson	KS	7/2/16 6:51	7/2/16 7:35	ML|ML|ML|ML|	|LS|ML|
accident	E	I-35 SB	TO 12TH ST	S	39.101881	-94.594093	Jackson	MO	7/3/16 7:08	7/3/16 7:37	|LE|ML|RE|	|ML|
minor accident	I	I-70 EB	PAST 31ST ST	E	39.072714	-94.531049	Jackson	MO	7/7/16 6:13	7/7/16 6:51	|LS|ML|ML|ML|RS|	|LS|ML|ML|
accident	I	I-70 EB	PAST FAIRFAX TRFWY	E	39.107515	-94.603604	Jackson	MO	7/12/16 5:50	7/12/16 6:37	|LS|ML|ML|ML|RE|RS	|RS|LS|ML|

TransSuite data portal

The TransSuite web-based Data Portal included the detector stations map and it was used to choose the detectors to obtain the traffic data as shown in Figure 4. Google maps were also used to determine the exact location of the bottlenecks and identify the detectors to collect the data. The data collection focused on typical bottleneck locations, and data downstream of the bottleneck were obtained for the capacity measurements. If congestion took place because of queue spillback from a downstream bottleneck, the capacity data were not analyzed further (9). Figures 5 and 6 are illustrations of incidents retrieved from Table 4. The event happened at I-435 WB, and upstream of Antioch Rd, so the detector with the red circle is located upstream and close enough to the event location.

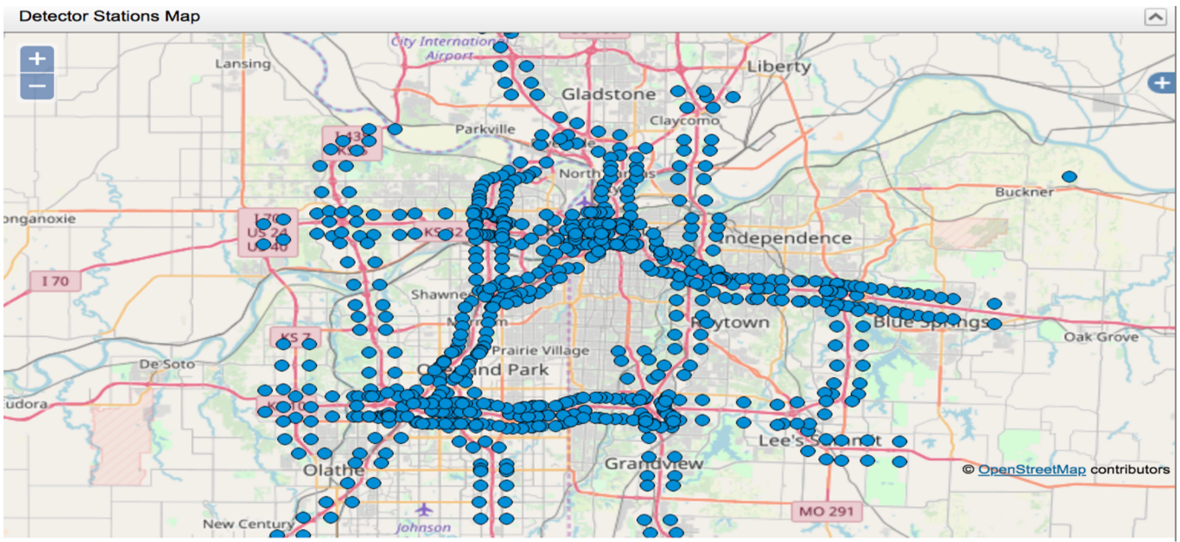

Figure 4 Detector Stations Map (retrieved from http://www.kcscout.com/KcDataPortal)

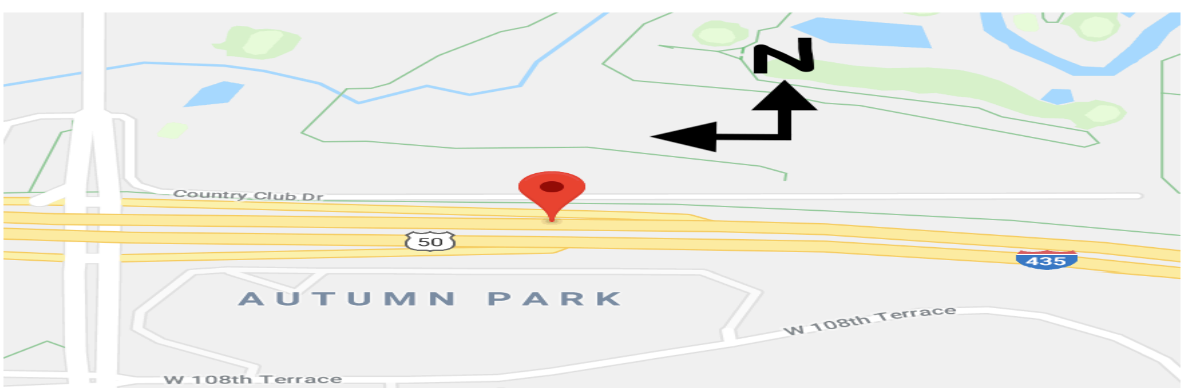

Figure 5 The exact location of the event, Google Maps

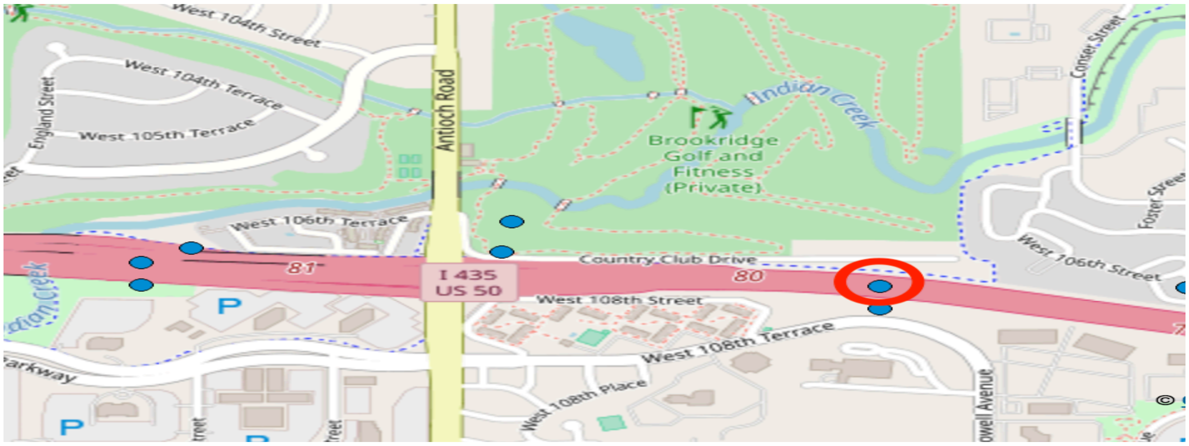

Figure 6 *The target detector, upstream from the event (retrieved from http://www.kcscout.com/KcDataPortal)*

3.2.2. Weather Underground

Weather data were obtained using historical records from the Weather Underground website. The Weather Underground website informs users about weather history of a particular area. Also, from this site, researchers can find hourly weather information during a specific day. Finally, only one weather category, "rain", was considered in the analysis, because snow events were not very frequent in the area.

3.3. Capacity and Speed Adjustment Factors

Following the HCM 2016 procedure, the effect of incidents and weather on capacity and Free-Flow Speed was converted as the default adjustment factors that affect the base conditions of a freeway segment. Those adjustment factors generally describe the remaining capacity for CAF, and the remaining FFS for the SAF. The final results include multiple adjustment factors, and were also compared with those from the HCM 2016.

3.3.1. Estimation of Capacity Adjustment Factors (CAF)

In order to estimate CAFs, the average breakdown and discharge flow were compared to the base conditions as follows:

- **CAF for bad weather conditions (rain) and no incident**

CAF was estimated as the ratio of the average breakdown flow during rain to the average breakdown flow during the base conditions, as a function of number of lanes.

- **CAF for incidents (good weather)**

CAF for incident conditions was estimated as the ratio of the average discharge flow during incidents to the average discharge flow during base conditions, as a function of the number of lanes as well as the measurement location (within or upstream of the lane closure).

CAF for rain and incident

CAF for both rain and incidents conditions was estimated as the ratio of the average discharge flow during the event of incident with rain, to the average discharge flow from the base conditions.

3.3.2. Estimation of Speed Adjustment Factors (SAF)

The FFS for the different conditions, rain no incident, incident, and incident with rain, were compared to the base Free-Flow Speed during the base conditions (good weather, no incident). As it was discussed previously, under non-incident conditions, FFS was defined as the average speed when the flow rate is as low as 1,000 veh/hr/ln. Also, for incident conditions, FFS was measured as the average speed during the incident period, assuming that the incident did not result in a traffic breakdown.

3.3.3. CAF and SAF results

The HCM 2016 assumes that when we compare two independent events that influence the capacity and the FFS, for example, rain and incidents, their combined effect can be estimated by multiplying the individual CAFs or SAFs (1). On the other hand, the methodology of this thesis resulted in multiple CAFs and SAFs, including the factors that were produced from the two combined events (incidents and adverse weather) at the same time. Next, the resulting adjustment factors were compared to those from the HCM 2016. Finally, two-sample t-tests were used to investigate the statistical difference between the different event groups.

3.4. Sample Size

The goal of the thesis was to collect data for two, three, and four lane directional freeways, considering also the measurement location, in case of incidents. As such, an effort was made to include at least 30 observations in each group. However, given the scattered and random occurrence of incidents, in some cases it was not possible to collect a large number of observations for each group, even if a large duration (4 years) was considered in this study.

4. DATA ANALYSIS

This section summarizes the procedures that were applied to collected data.

4.1. Data Organization

Traffic data were first arranged as non-incident or incident conditions. Under each group, two sub-groups that included good weather or rain were generated (Figure 7). In addition, as shown in Figure 8, each sub-group was further divided based on the number of freeway lanes in each direction (two, three, or four lanes), as well as the incident type (upstream of closure, within closure).

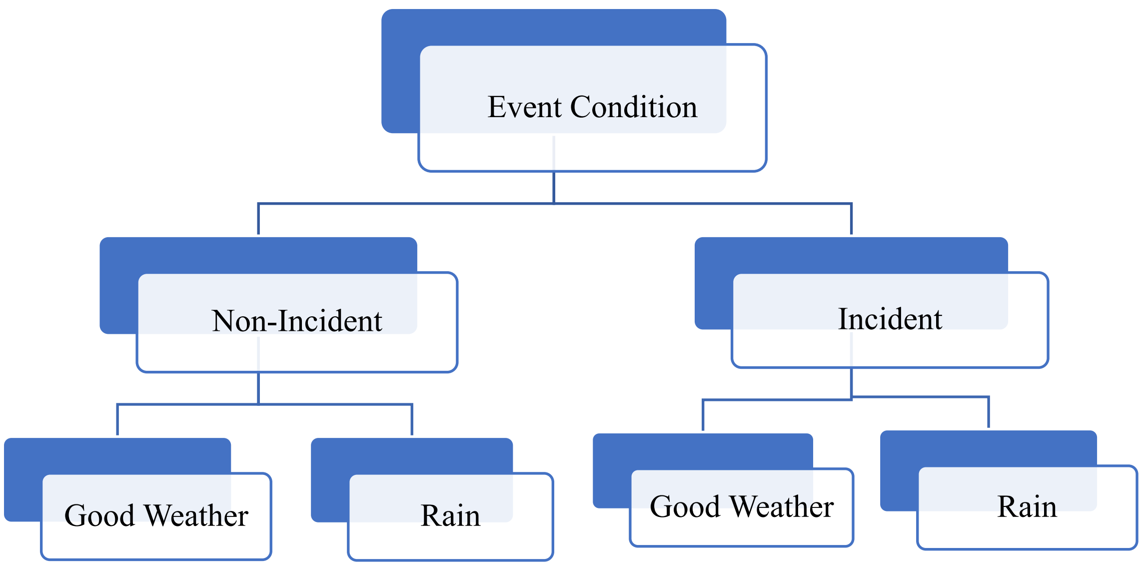

Figure 7 Event Classifications

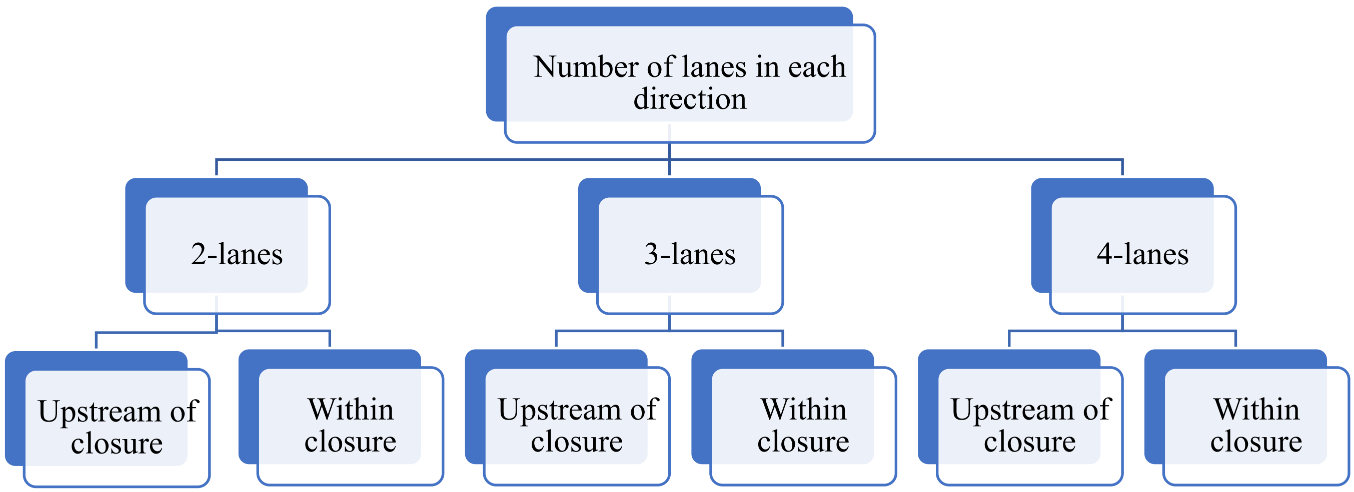

Figure 8 The hierarchy of the selected facility type for incident condition

4.1.1. Incident with sensor upstream of lane closure

This case included incident events where the nearest upstream sensor was located upstream of the lane closure (Figure 9). However, this did not mean that the sensor was far away from the incident location, since the breakdown time recorded in the sensor matched with the event time from the event report. Although this type of incidents is associated with lane closure from the event viewer report, the sensor is located further upstream from the closure, and it captures the queued vehicles at that location due to the incident event.

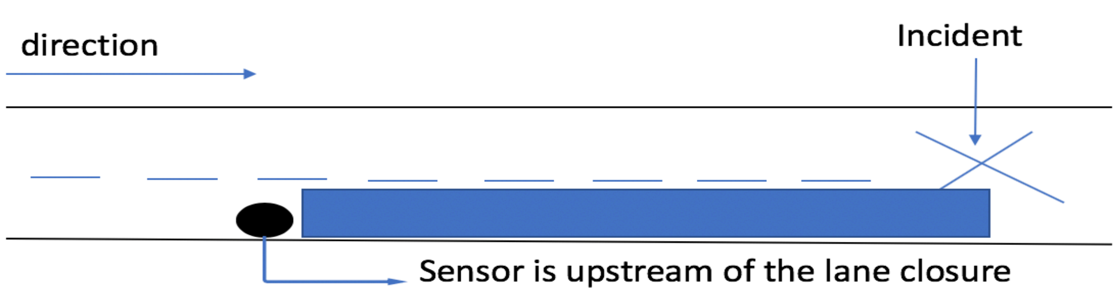

Figure 9 Incident with Sensor Upstream of a Lane Closure.

4.1.2. Incident with sensor within lane closure

This case included incident events where the sensor was located upstream of the incident, but within the lane closure (Figure 10). In this case, the sensor data matched the event viewer information, in that the measurement point was within the lane closure. Similar to the previous situation, the breakdown times from the sensor matched those from the event record.

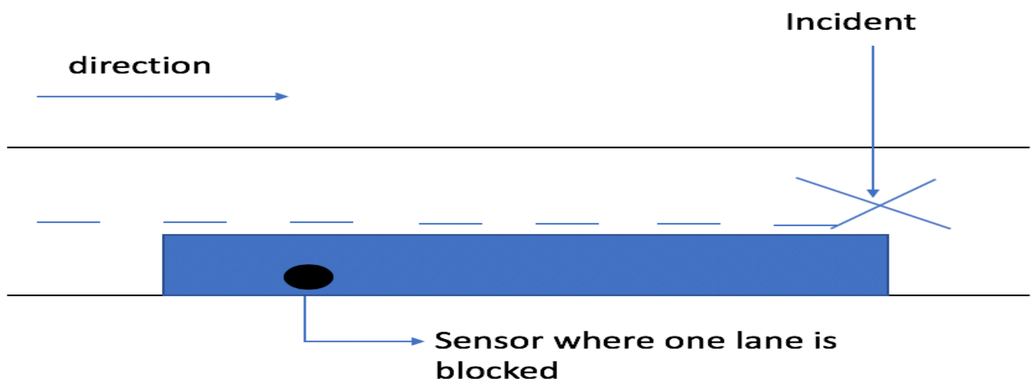

Figure 10 Incident with Sensor within Lane Closure

4.2. Data Reduction and Screening

Data were screened to ensure that they represent breakdown conditions during an event, as described earlier. If an inquiry from a detector did not match the timeline of the event from the event viewer report, it was excluded from the analysis. According to Elefteriadou (11), the congestion duration should be at least for 15 minutes (11). Breakdowns that occurred at an average flow rate of less than 1,300 veh/hr/ln for non-incident scenarios, and the average discharge flow rate for incident events less than 900 veh/hr/ln, were also removed as these were considered as extremely low. Finally, the data quality is an important indicator of the detector performance, so data quality less than 80% as provided by KC SCOUT was not utilized for this thesis.

4.3. Two Samples T-Test

T-tests were applied to determine whether the difference between the mean capacities found in the sample data is significantly different. The null hypothesis states that there is no difference between the two population means (e.g., capacity between base conditions and incidents), and the alternative hypotheses states that there is a difference. A 95% confidence level was used.

H_o: $\mu_1 = \mu_2$

H_a: $\mu_1 \neq \mu_2$

Where:

μ_1 mean capacity for base conditions

μ_2: mean capacity for rain, incident, or rain and incident conditions

4.4. SAFs and CAFs Results

Tables for each category were developed:

- As a function of the number of lanes and measurement location (within or upstream of the lane closure), tables for CAFs and SAFs for incident conditions (incidents or incidents with rain).

5. RESULTS

This chapter presents the results of the data analysis. Data were collected to find incident events for each category (e.g., rain with incident for three lanes) for each lane blockage. After that, the data from the same location were collected for the base scenario (i.e., congestion that was not caused by incidents and during good weather). Figure 11 shows how each event for the study was reported. Breakdown or discharge flow rates per lane and average across all lanes were reported in 5-minute intervals and converted to hourly volumes. Weather data were reported hourly.

Capacity Adjustment Factors (CAF) and Speed Adjustment Factors (SAF) were developed by comparing their averages during base conditions with their averages during rain, and for non-incident events. Also, similar adjustment factors were developed as a function of incidents by number of lanes by comparing the base conditions to incidents-only and incidents with rain. Thus, t-tests were performed between these conditions to investigate potential differences between the average capacities and speeds under base conditions, and the remaining conditions. Finally, tables for CAF and SAF are also presented.

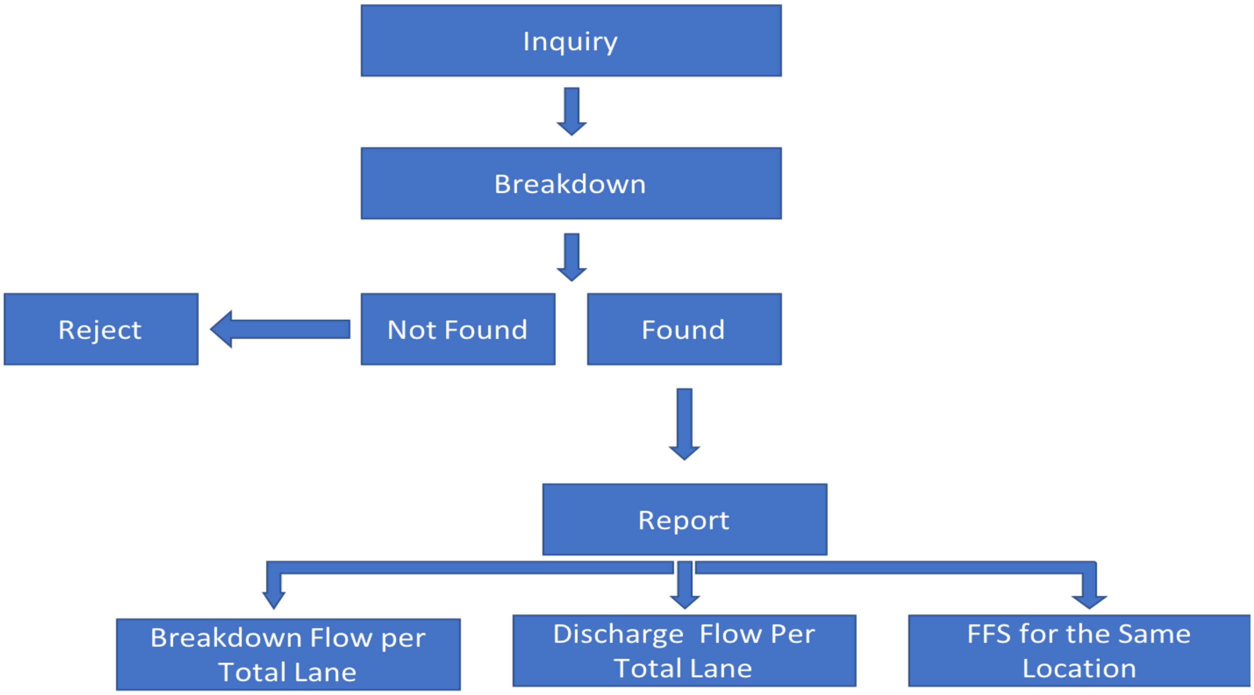

Figure 11 Steps for Reporting an Event

5.1. Capacity Results

This section presents the average capacity observed from each detector by facility type (e.g., two-lane freeway). Four conditions are presented here:

1- Observed Pre-Breakdown Flow for Base Conditions.

2- Observed Discharge Flow During Incident Conditions (good weather);

- Incidents Capacity (upstream of closure)
- Incident Capacity (within closure)

3- Observed Pre-Breakdown Flow During Rain (no incidents)

4- Observed Discharge Flow During Rain and Incidents;

- Rain and incidents capacity (upstream of closure)
- Rain and incident capacity (within closure)

5.1.1. Capacity for Base Conditions

The average breakdown flow was used to define capacity during base conditions for two-lane, three-lane, and four-lane freeway segments, as shown in Table 5, Table 6, and Table 7, respectively.

- **Two-Lanes**

Twenty-nine events were observed during base conditions for two-lane segments, and these are listed in Table 6. The data were collected at segments along I-70 and I-35. The average breakdown flow was found to be 3,291 veh/hr, while the average breakdown flow per lane was 1,645 veh/hr/ln.

Table 6 Base Conditions Capacity for Two-Lane Segments (Good Weather No Incidents)

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow per Lane (veh/hr/ln)
I-70 E @ WEST OF MO7	2	3352	1676
I-70 E @ WEST OF MO7	2	3685	1843
I-70 E @ WEST OF MO7	2	3026	1513
I-70 E @ WEST OF MO7	2	3552	1776
I-70 E @ WEST OF MO7	2	3348	1674
I-35 S @ 159TH STREET	2	2580	1290
I-70 E @ WEST OF MO7	2	3528	1764
I-70 E @ WEST OF MO7	2	3012	1506
I-70 E @ WEST OF MO7	2	3660	1830
I-70 E @ WEST OF MO7	2	3540	1770
I-70 E @ WEST OF MO7	2	3327	1664
I-70 E @ WEST OF MO7	2	3324	1662
I-70 E @ WEST OF MO7	2	3359	1680
I-70 E @ WEST OF MO7	2	3144	1572
I-70 E @ WEST OF MO7	2	3359	1680
I-70 E @ WEST OF MO7	2	2984	1492
I-70 E @ WEST OF MO7	2	3540	1770
I-70 E @ WEST OF MO7	2	3777	1889
I-70 E @ WEST OF MO7	2	3613	1807
I-70 E @ WEST OF MO7	2	3108	1554
I-70 E @ WEST OF MO7	2	3627	1814
I-70 E @ WEST OF MO7	2	3760	1880
I-70 E @ WEST OF MO7	2	3168	1584
I-35 N @ AT PASEO BLVD	2	2448	1224

I-35 N @ AT PASEO BLVD	2	3240	1620
I-35 N @ AT PASEO BLVD	2	2916	1458
I-35 N @ AT PASEO BLVD	2	3216	1608
I-35 N @ AT PASEO BLVD	2	3107	1554
I-35 N @ AT PASEO BLVD	2	3132	1566
Average		3291	1645
Standard Deviation		326	163

- **Three-Lane**

Breakdown flow rates for three-lanes are listed in Table 7. Forty-seven capacity observations were collected during base conditions. Average breakdown flow obtained was 5,237 veh/hr. and average breakdown flow per lane was 1,746 veh/hr/ln.

Table 7 Base Conditions Capacity for Three-Lane Segments (Good Weather No Incidents)

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow per Lane (veh/hr/ln)
I-70 W @ BEFORE STADIUM DRIVE	3	5232	1744
I-70 W @ BEFORE STADIUM DRIVE	3	5257	1752
I-70 W @ NW 19TH STREET	3	4342	1447
I-70 W @ BEFORE STADIUM DRIVE	3	5158	1719
I-70 W @ BEFORE STADIUM DRIVE	3	5672	1891
I-70 W @ BEFORE STADIUM DRIVE	3	5158	1719
I-70 E @ EAST OF BLUE RIDGE	3	5768	1923
I-70 E @ EAST OF BLUE RIDGE	3	5949	1983
I-70 E @ EAST OF BLUE RIDGE	3	5615	1872
I-70 E @ EAST OF BLUE RIDGE	3	5256	1752
I-70 E @ EAST OF BLUE RIDGE	3	5520	1840
I-70 E @ EAST OF BLUE RIDGE	3	5561	1854
I-70 E @ NW SCRIMSHAW RD	3	5673	1891
I-70 E @ NW SCRIMSHAW RD	3	4212	1404
I-70 E @ NW SCRIMSHAW RD	3	5517	1839
I-70 E @ NW SCRIMSHAW RD	3	5019	1673
I-70 E @ NW SCRIMSHAW RD	3	4368	1456
I-70 W @ NW 50TH ST	3	4884	1628
I-70 W @ NW 50TH ST	3	5496	1832
I-70 W @ NW 50TH ST	3	5173	1724
I-70 W @ NW 50TH ST	3	4895	1632
I-35 S @ 127TH STREET	3	5498	1833
I-35 S @ 127TH STREET	3	4612	1537
I-35 S @ 127TH STREET	3	4920	1640
I-35 S @ 127TH STREET	3	5729	1910

I-35 S @ 127TH STREET	3	6525	2175
I-35 S @ QUIVIRA RD	3	3948	1316
I-35 S @ QUIVIRA RD	3	4392	1464
I-35 S @ 75TH ST	3	5344	1781
I-35 S @ 75TH ST	3	5800	1933
I-35 S @ 75TH ST	3	5820	1940
I-35 S @ LAMAR AVE	3	5736	1912
I-35 S @ LAMAR AVE	3	5523	1841
I-35 S @ LAMAR AVE	3	5568	1856
I-35 S @ LAMAR AVE	3	5913	1971
I-35 N @ MISSION ROAD	3	5076	1692
I-35 N @ MISSION ROAD	3	5316	1772
I-35 N @ MISSION ROAD	3	5172	1724
I-35 N @ MISSION ROAD	3	4704	1568
I-435 E @ BEFORE QUIVIRA ROAD	3	4872	1624
I-435 E @ BEFORE QUIVIRA ROAD	3	5148	1716
I-435 W @ SOUTH OF 63RD ST	3	5204	1735
I-435 N @ SOUTH OF 210 HIGHWAY	3	4752	1584
I-435 N @ SOUTH OF 210 HIGHWAY	3	4524	1508
I-435 N @ SOUTH OF 210 HIGHWAY	3	4767	1589
I-435 S @ 79TH STREET	3	5706	1902
I-435 S @ 79TH STREET	3	5839	1946
Average		5237	1746
Standard Deviation		531	177

- **Four-Lane**

Pre-breakdown flow data were observed along I-70, I-35, and I-435 as listed in Table 8. Average breakdown flow observed during base conditions was 6,531 veh/hr, or equivalently 1,633 veh/hr/ln.

Table 8 Base Conditions Capacity for Four-Lane Segments (Good Weather No Incidents)

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow per Lane (veh/hr/ln)
I-70 E @ AT LITTLE BLUE	4	5424	1356
I-70 E @ AT LITTLE BLUE	4	5580	1395
I-70 E @ AT LITTLE BLUE	4	5376	1344
I-70 E @ BROOKLYN AVE	4	7340	1835
I-35 S @ 67TH ST	4	6600	1650
I-35 S @ 67TH ST	4	6819	1705
I-35 S @ 67TH ST	4	5754	1439
I-35 S @ 67TH ST	4	6562	1641

I-35 S @ 67TH ST	4	6802	1701
I-35 S @ 67TH ST	4	6636	1659
I-35 S @ 67TH ST	4	7277	1819
I-35 S @ I-636	4	6747	1687
I-35 S @ I-637	4	6798	1700
I-35 S @ I-640	4	6864	1716
I-35 S @ JOHNSON DR	4	6738	1685
I-35 S @ JOHNSON DR	4	5760	1440
I-35 S @ JOHNSON DR	4	6744	1686
I-35 S @ JOHNSON DR	4	6796	1699
I-435 E @ WEST OF 104TH ST	4	7084	1771
I-435 E @ WEST OF 104TH ST	4	7368	1842
I-435 E @ WEST OF 104TH ST	4	7020	1755
I-435 S @ Front Street	4	5594	1399
Average		6531	1633
Standard Deviation		638	160

5.1.2. Incident Capacity (Good Weather)

The average discharge flow rate was used to measure capacity during incidents. The first capacity in each table presents the average capacity per the total (open) lanes (veh/hr), which were then converted to the average capacity per open lane during incidents (veh/hr/ln). Each table shows the number of lanes that the facility initially had, and then the number of lanes that were not affected during the incidents. Finally, t-tests were carried out between incidents measured upstream of the lane closure and incidents measured within the lane closure to identify whether the measurement location had an influence on the capacity during incidents.

- **Two-lane Incidents Measured Upstream of Lane Closure**

Two-lane incidents measured upstream of lane closure were observed at twelve locations over Kansas City's freeways, as shown in Table 9. The average discharge flow was found to be 2,098 veh/hr, or 1,098 veh/hr/ln per open lane.

Table 9 Incident Capacity for Two-Lanes Measured Upstream of Closures (Good Weather)

Detector	Number of Lanes	Discharge flow (veh/hr)	Number of Open Lanes	Discharge flow per lane (veh/hr/ln)
I-70 W @ 23RD ST	2	2832	2	1416
I-35 S @ BEFORE PASEO BLVD	2	3216	2	1608
I-70 E @ WEST OF MO7	2	1656	2	828
I-470 S @ NORTH OF WOODS CHAPEL ROAD	2	2556	2	1278
US-71 S @ SOUTH OF 75TH STREET	2	1716	2	858
I-470 N @ NORTH OF LAKEWOOD BLVD	2	1956	2	978
US-50 W @ CHIPMAN ROAD	2	2628	2	1314
I-470 N @ NORTH OF LAKEWOOD BLVD	2	1620	2	810
I-70 E @ 110TH STREET	2	1176	2	1176
I-70 E @ EAST OF MO-7	2	2040	2	1020
I-70 E @ EAST OF MO-7	2	1620	2	810
I-70 E @ EAST OF MO-7	2	2160	2	1080
Average		2098		1098
Standard Deviation		680		287

- **Two-lanes Incidents Measured Within Lane Closure**

Only six events were found for two-lane incidents measured within a lane closure, as shown in Table 10. The average discharge flow was 1,111 veh/h or 1,111 veh/h/ln.

Table 10 Incident Capacity for Two-Lanes Measured within Closures (Good Weather)

Detector	Number of Lanes	Capacity (veh/hr)	Number of Open Lanes	Capacity per open lane (veh/hr/ln)
I-470 N @ I-70	2	984	1	984
US-69 S @ 135TH STREET LOOP RAMP	2	960	1	960
I-635 N @ MISSOURI RIVER	2	1284	1	1284
I-470 S @ NORTH OF WOODS CHAPEL ROAD	2	1272	1	1272
US-71 S @ 75TH STREET	2	1356	1	1356
I-70 E @ EAST OF MO-7	2	810	1	810
AVERAGE		1111		1111
STANDARD DEVIATION		222		222

Table 11 shows the results of the t-test. Assuming a 95% confident interval, the difference between incident capacities measured upstream and within a lane closure is not statistically significant, as the two-tailed p-value is higher than 0.025. Thus, our analysis showed that the measurement location did not affect the incident capacity results at two-lane segments. As a result, the observations from Table 9 and Table 10 were merged into Table 12.

Table 11 Two-Lanes T-Statistic Between Incidents without Lane Closure and with One Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1098	1111
N	12	6
Std. Deviation	287	222
Std. Error Mean	83	54

	Degrees of Freedom	T-score	P value (2-tailed)
Incidents upstream closure-incidents within closure	16	0.0969	0.924

According to Table 12, the average discharge flow per open lane was 1,102 veh/hr/ln.

Table 12 Incident Capacity for Two-Lanes

Detector	Number of Lanes	Discharge Flow per open lane (veh/hr/ln)
I-70 W @ 23RD ST	2	1416
I-35 S @ BEFORE PASEO BLVD	2	1608
I-70 E @ WEST OF MO7	2	828
I-470 S @ NORTH OF WOODS CHAPEL ROAD	2	1278
US-71 S @ SOUTH OF 75TH STREET	2	858
I-470 N @ NORTH OF LAKEWOOD BLVD	2	978
US-50 W @ CHIPMAN ROAD	2	1314
I-470 N @ NORTH OF LAKEWOOD BLVD	2	810
I-70 E @ 110TH STREET	2	1176
I-70 E @ EAST OF MO-7	2	1020
I-70 E @ EAST OF MO-7	2	810
I-70 E @ EAST OF MO-7	2	1080
I-470 N @ I-70	2	984
US-69 S @ 135TH STREET LOOP RAMP	2	960
I-635 N @ MISSOURI RIVER	2	1284
I-470 S @ NORTH OF WOODS CHAPEL ROAD	2	1272
US-71 S @ 75TH STREET	2	1356
I-70 E @ EAST OF MO-7	2	810
Average		1102
Standard Deviation		244

- **Three-Lanes Incidents Measured Upstream of Lane Closure**

Twenty-nine locations were found for the three lane segments with incidents measured upstream of the lane closure, as shown in Table 13. The average discharge flow was 3,910 veh/hr and was converted to average discharge flow per open lane as 1,303 veh/hr/ln.

Table 13 Incident Capacity for Three-Lanes Measured Upstream of Closure (Good Weather)

Detector	Number of Lanes	Discharge flow (veh/hr)	Number of Open Lanes	Discharge flow per open lane (veh/hr/ln)
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	3252	3	1084
I-70 E @ NW SCRIMSHAW RD	3	3900	3	1300
I-70 E @ NW SCRIMSHAW RD	3	4920	3	1640
I-35 S @ 75TH ST	3	5592	3	1864
I-35 S @ 75TH ST	3	5064	3	1688
I-35 S @ 75TH ST	3	5016	3	1672
I-35 S @ LAMAR AVE	3	3036	3	1012
I-35 S @ LAMAR AVE	3	3612	3	1204
I-70 W @ NW 50TH ST	3	4284	3	1428
I-35 S @ 127TH STREET	3	3348	3	1116
I-35 S @ 127TH STREET	3	3024	3	1008
I-35 N @ MISSION ROAD	3	3624	3	1208
I-35 N @ MISSION ROAD	3	4104	3	1368
I-70 W @ BEFORE STADIUM DRIVE	3	3936	3	1312
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	3804	3	1268
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	4056	3	1352
I-35 S @ 75TH ST	3	4128	3	1376
I-35 S @ 75TH ST	3	4572	3	1524
I-35 N @ MISSION ROAD	3	3624	3	1208
I-35 N @ MISSION ROAD	3	4152	3	1384
I-435 E @ BEFORE QUIVIRA ROAD	3	3420	3	1140
I-435 E @ BEFORE QUIVIRA ROAD	3	3024	3	1008

I-435 E @ BEFORE QUIVIRA ROAD	3	3744	3	1248
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	3336	3	1112
I-70 W @ NW 19TH STREET	3	3336	3	1112
I-70 W @ BEFORE STADIUM DRIVE	3	3324	3	1108
I-35 S @ LAMAR AVE	3	5496	3	1832
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	3312	3	1104
I-70 E @ EAST OF CHRYSLER AVE	3	3336	3	1112
Average		3910		1303
Standard Deviation		731		244

- **Three-Lanes Incidents Measured Within Lane Closure**

Table 14 shows fifteen incidents measured within the lane closure that were observed at three-lane segments at multiple locations across Kansas City. The average discharge flow was 2,613 veh/hr. Additionally, the average discharge flow per open lane was found to be 1,306 veh/hr/ln.

Table 14 Incident Capacity for Three-Lane Measured Within Lane Closure (Good Weather and One Closure)

Detector	Number of Lanes	discharge flow (veh/hr)	Number of Open Lanes	discharge flow per open lane (veh/hr/ln)
I-35 S @ 127TH STREET	3	3096	2	1548
I-35 S @ 127TH STREET	3	3168	2	1584
I-35 S @ 127TH STREET	3	2196	2	1098
I-35 S @ 127TH STREET	3	2388	2	1194
I-35 S @ QUIVIRA RD	3	2712	2	1356
I-70 E @ NW SCRIMSHAW RD	3	2016	2	1008
I-70 W @ NW 50TH ST	3	2508	2	1254
I-35 S @ QUIVIRA RD	3	2976	2	1488
I-35 N @ MISSION ROAD	3	2040	2	1020
I-35 S @ 75TH ST	3	2424	2	1212
I-70 W @ NW 50TH ST	3	2712	2	1356

I-35 N @ MISSION ROAD	3	2652	2	1326
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	2052	2	1026
I-470 W @ VIEW HIGH ROAD	3	3156	2	1578
I-35 N @ ANTIOCH RD	3	3096	2	1548
Average		2613		1306
Standard Deviation		422		211

T-test results shown in Table 15 indicated that the difference between incident capacities measured upstream and within the lane closure is not statistically significant as the p-value is greater than 0.025. Thus, our analysis indicated that the measurement location did not have a significant effect on the capacity at three-lane segments evaluated during incidents at the study locations. A new table was therefore, developed to combine the observations from Table 13 and Table 14 into Table 16.

Table 15 Three-Lanes T-Statistic Between Incidents Measured Upstream and Within Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1303	1306
N	29	15
Std. Deviation	244	211
Std. Error Mean	45	55

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Incidents upstream closure-incidents within closure	42	0.0404	0.968

The results shown in Table 16 were retrieved from combining Table 13 and Table 14. The average discharge flow per open lane was 1,304 veh/hr/ln.

Table 16 Three-Lanes Incidents Capacity

Detector	Number of Lanes	Discharge Flow per open lane (veh/hr/ln)
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1084
I-70 E @ NW SCRIMSHAW RD	3	1300
I-70 E @ NW SCRIMSHAW RD	3	1640
I-35 S @ 75TH ST	3	1864
I-35 S @ 75TH ST	3	1688
I-35 S @ 75TH ST	3	1672
I-35 S @ LAMAR AVE	3	1012
I-35 S @ LAMAR AVE	3	1204
I-70 W @ NW 50TH ST	3	1428
I-35 S @ 127TH STREET	3	1116
I-35 S @ 127TH STREET	3	1008
I-35 N @ MISSION ROAD	3	1208
I-35 N @ MISSION ROAD	3	1368
I-70 W @ BEFORE STADIUM DRIVE	3	1312
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1268
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1352
I-35 S @ 75TH ST	3	1376
I-35 S @ 75TH ST	3	1524
I-35 N @ MISSION ROAD	3	1208
I-35 N @ MISSION ROAD	3	1384
I-435 E @ BEFORE QUIVIRA ROAD	3	1140
I-435 E @ BEFORE QUIVIRA ROAD	3	1008
I-435 E @ BEFORE QUIVIRA ROAD	3	1248
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1112
I-70 W @ NW 19TH STREET	3	1112
I-70 W @ BEFORE STADIUM DRIVE	3	1108
I-35 S @ LAMAR AVE	3	1832
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1104
I-70 E @ EAST OF CHRYSLER AVE	3	1112
I-35 S @ 127TH STREET	3	1548
I-35 S @ 127TH STREET	3	1584
I-35 S @ 127TH STREET	3	1098
I-35 S @ 127TH STREET	3	1194
I-35 S @ QUIVIRA RD	3	1356
I-70 E @ NW SCRIMSHAW RD	3	1008
I-70 W @ NW 50TH ST	3	1254

I-35 S @ QUIVIRA RD	3	1488
I-35 N @ MISSION ROAD	3	1020
I-35 S @ 75TH ST	3	1212
I-70 W @ NW 50TH ST	3	1356
I-35 N @ MISSION ROAD	3	1326
I-70 E @ EAST OF BLUE RIDGE CUTOFF	3	1026
I-470 W @ VIEW HIGH ROAD	3	1578
I-35 N @ ANTIOCH RD	3	1548
Average		1304
Standard Deviation		231

- **Four-Lanes Incidents Measured Upstream of Lane Closure**

Incidents measured upstream of lane closure during good weather were obtained from twenty-four detectors located on several freeways across Kansas City. The majority of the events were observed on I-35. The average discharge flow was 5,001 veh/hr and the average discharge flow per lane was 1,250 veh/hr/ln (Table 17).

Table 17 Incident Capacity for Four-Lanes Measured Upstream of Closures (Good Weather)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge flow per open lane (veh/hr/ln)
I-70 E @ AT LITTLE BLUE	4	4152	4	1038
I-35 S @ 67TH ST	4	5316	4	1329
I-35 S @ I-635	4	5364	4	1341
I-35 S @ 67TH ST	4	5292	4	1323
I-35 S @ 67TH ST	4	4500	4	1125
I-35 S @ 67TH ST	4	5328	4	1332
I-35 S @ 67TH ST	4	5028	4	1257
I-35 S @ 67TH ST	4	5256	4	1314
I-35 S @ 67TH ST	4	5556	4	1389
I-35 S @ I-635	4	4776	4	1194
I-35 S @ I-635	4	4416	4	1104
I-35 S @ JOHNSON DR	4	4344	4	1086

I-435 E @ WEST OF 104TH ST	4	5172	4	1293
I-435 E @ STATE LINE RD	4	5988	4	1497
I-35 S @ 67TH ST	4	4896	4	1224
I-35 S @ I-635	4	6204	4	1551
I-35 S @ I-635	4	4848	4	1212
I-35 S @ 67TH ST	4	4236	4	1059
I-35 S @ 67TH ST	4	4020	4	1005
I-35 S @ 67TH ST	4	4296	4	1074
I-35 S @ I-635	4	4896	4	1224
I-435 E @ WEST OF 104TH ST	4	4572	4	1143
I-435 E @ STATE LINE RD	4	6156	4	1539
I-35 N @ NORTH OF ROE AVE	4	5400	4	1350
Average		5001		1250
Standard Deviation		619		155

- **Four-Lanes Incidents Measured Within Lane Closure**

Over fifteen locations shown in Table 18 include four-lanes incidents measured within the lane closure at I-35, I-70, and I-435. It was found that the average discharge flow (i.e., capacity) was 3,807 veh/hr, and the average discharge flow per open lane was 1,269 veh/hr/ln.

Table 18 Incident Capacity for Four-Lane with One Lane Closures (Good Weather)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge flow per open lane (veh/hr/ln)
I-70 E @ AT LITTLE BLUE	4	3744	3	1248
I-70 W @ AT LITTLE BLUE RIVER	4	3660	3	1220
I-435 E @ WEST OF 104TH ST	4	4008	3	1336
I-70 E @ AT LITTLE BLUE	4	4356	3	1452
I-70 W @ AT LITTLE BLUE RIVER	4	3108	3	1036
I-70 W @ AT LITTLE BLUE RIVER	4	3912	3	1304

I-35 S @ 67TH ST	4	4836	3	1612
I-35 S @ I-635	4	3240	3	1080
I-35 S @ JOHNSON DR	4	3204	3	1068
I-435 E @ WEST OF 104TH ST	4	4248	3	1416
I-70 E @ BROOKLYN AVE	4	4020	3	1340
I-70 W @ AT LITTLE BLUE RIVER	4	3828	3	1276
I-70 E @ BROOKLYN AVE	4	3420	3	1140
I-435 E @ WEST OF 104TH ST	4	3300	3	1100
I-35 S @ ANTIOCH RD	4	4224	3	1408
Average		3807		1269
Standard Deviation		495		165

Table 19 displays the results from the t-test. With a 95% confidence interval, the results indicated that the difference between incident capacities measured upstream and within the lane closure is not statistically significant. As a result, the analysis from this thesis indicated that the measurement location did not have a significant effect on the capacity at four-lane segments evaluated during incidents at the study locations. Thus, a new table was created by combining the values from Table 17and Table 18.

Table 19 Four-Lanes T-Statistic Between Incidents Measured Upstream and Within Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1250	1269
N	24	15
Std. Deviation	155	165
Std. Error Mean	32	37

	Degree of Freedom	T-score	P value (2-tailed)
Incidents upsteam closure-incidents within closure	37	0.3634	0.7184

According to the combined results shown in Table 20, the average discharge flow per lane was 1,257 veh/hr/ln.

Table 20 Four-Lanes Incidents Capacity

Detector	Number of Lanes	Discharge Flow per open lane (veh/hr/ln)
I-70 E @ AT LITTLE BLUE	4	1038
I-35 S @ 67TH ST	4	1329
I-35 S @ I-635	4	1341
I-35 S @ 67TH ST	4	1323
I-35 S @ 67TH ST	4	1125
I-35 S @ 67TH ST	4	1332
I-35 S @ 67TH ST	4	1257
I-35 S @ 67TH ST	4	1314
I-35 S @ 67TH ST	4	1389
I-35 S @ I-635	4	1194
I-35 S @ I-635	4	1104
I-35 S @ JOHNSON DR	4	1086
I-435 E @ WEST OF 104TH ST	4	1293
I-435 E @ STATE LINE RD	4	1497
I-35 S @ 67TH ST	4	1224
I-35 S @ I-635	4	1551
I-35 S @ I-635	4	1212
I-35 S @ 67TH ST	4	1059
I-35 S @ 67TH ST	4	1005
I-35 S @ 67TH ST	4	1074
I-35 S @ I-635	4	1224
I-435 E @ WEST OF 104TH ST	4	1143
I-435 E @ STATE LINE RD	4	1539
I-35 N @ NORTH OF ROE AVE	4	1350

I-70 E @ AT LITTLE BLUE	4	1248
I-70 W @ AT LITTLE BLUE RIVER	4	1220
I-435 E @ WEST OF 104TH ST	4	1336
I-70 E @ AT LITTLE BLUE	4	1452
I-70 W @ AT LITTLE BLUE RIVER	4	1036
I-70 W @ AT LITTLE BLUE RIVER	4	1304
I-35 S @ 67TH ST	4	1612
I-35 S @ I-635	4	1080
I-35 S @ JOHNSON DR	4	1068
I-435 E @ WEST OF 104TH ST	4	1416
I-70 E @ BROOKLYN AVE	4	1340
I-70 W @ AT LITTLE BLUE RIVER	4	1276
I-70 E @ BROOKLYN AVE	4	1140
I-435 E @ WEST OF 104TH ST	4	1100
I-35 S @ ANTIOCH RD	4	1408
Average		1257
Standard Deviation		157

In summary, the measurement location during an incident was not found to affect the good weather incident capacity, irrespective of the number of freeway lanes.

5.1.3. Capacity for Adverse Weather (Rain and No Incidents)

The capacity measurement during rain and no incidents is the same as the base conditions as the average pre-breakdown flow rate was used for that measurement. Also, the average pre-breakdown flow per lane was calculated and listed in Table 20, Table 21, and Table 23.

- **Two-Lanes**

Table 21 shows the thirteen events obtained during congestion with rain at two-lane freeways. The average breakdown flow (i.e., capacity) was 3,248 veh/hr. Also, average capacity per lane was 1,624 veh/hr/ln.

Table 21 Two-Lane Capacity During Adverse Weather (Rain) and no Incidents

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow (veh/hr/ln)
US-50 W @ 291 HIGHWAY NORTH	2	3169	1585
I-70 E @ WEST OF MO7	2	3564	1782
I-35 S @ 159TH STREET	2	2364	1182
I-35 S @ 159TH STREET	2	2580	1290
US-69 N @ 119TH STREET	2	3456	1728
US-69 N @ 119TH STREET	2	2844	1422
US-69 N @ COLLEGE	2	3468	1734
US-69 N @ COLLEGE	2	3060	1530
US-69 N @ COLLEGE	2	3132	1566
US-69 N @ COLLEGE	2	3984	1992
US-69 N @ COLLEGE	2	3528	1764
US-71 S @ SOUTH OF 75TH STREET	2	3336	1668
US-71 S @ SOUTH OF 75TH STREET	2	3744	1872
AVERAGE		3248	1624
Standard Deviation		457	229

- **Three-Lanes**

Several detectors located at three-lane freeways across Kansas City collected the traffic data for congestion during rain. The data were then summarized in Table 22. Twenty events were observed during rain and no incidents. The average breakdown flow (i.e., capacity) was 5,078 veh/hr, or 1,693 veh/hr/ln.

Table 22 Three-Lane Capacity During Adverse Weather (Rain) and no Incidents

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow (veh/hr/ln)
I-70 W @ NOLAND ROAD	3	4680	1560
I-70 W @ NOLAND ROAD	3	4992	1664
I-70 W @ NOLAND ROAD	3	5071	1690
I-70 W @ NW 50TH ST	3	4344	1448
I-35 S @ 75TH ST	3	5316	1772
I-35 S @ 75TH ST	3	4296	1432
I-35 S @ 75TH ST	3	6369	2123
I-35 S @ LAMAR AVE	3	5688	1896
I-35 S @ LAMAR AVE	3	5208	1736
I-35 S @ LAMAR AVE	3	5052	1684
I-35 S @ LAMAR AVE	3	5271	1757
I-35 N @ NORTH OF I-435	3	4308	1436
I-435 S @ 79TH STREET	3	5390	1797
I-35 S @ LAMAR AVE	3	4380	1460
I-35 S @ LAMAR AVE	3	4668	1556
I-35 S @ 127th Street	3	6075	2025
I-435 S @ 79TH STREET	3	4907	1636
I-70 W @ NW 50TH ST	3	5436	1812
I-35 S @ 75TH ST	3	5503	1834
I-35 S @ 75TH ST	3	4608	1536
AVERAGE		5078	1693
Standard Deviation		579	193

- **Four-Lanes**

The average four-lanes capacity during rain and no incidents obtained from sixteen locations was 6,505 veh/hr, while the per-lane capacity was 1,626 veh/hr/ln (Table 23).

Table 23 Four-Lane Capacity During Adverse Weather (Rain) and no Incidents

Detector	Number of Lanes	Breakdown Flow (veh/hr)	Breakdown Flow (veh/hr/ln)
I-70 E @ BROOKLYN AVE	4	6012	1503
I-35 S @ I-635	4	6917	1729
I-35 S @ I-635	4	5856	1464
I-35 S @ JOHNSON DR	4	6468	1617
I-35 S @ JOHNSON DR	4	5484	1371
I-35 S @ JOHNSON DR	4	5436	1359
I-35 S @ JOHNSON DR	4	5616	1404
I-435 W @ WEST OF WORNALL RD	4	6819	1705
I-435 W @ WEST OF WORNALL RD	4	7416	1854
I-435 W @ WEST OF WORNALL RD	4	7504	1876
I-435 E @ STATE LINE RD	4	6649	1662
I-435 E @ STATE LINE RD	4	6881	1720
I-435 E @ STATE LINE RD	4	6336	1584
I-435 E @ STATE LINE RD	4	7135	1784
I-435 E @ WEST OF 104TH ST	4	6648	1662
I-435 E @ WEST OF 104TH ST	4	6900	1725
AVERAGE		6505	1626
Standard Deviation		658	165

In this section, the average per lane pre-breakdown flow was observed during rain and no incidents for two, three, and four lanes. Average capacity during adverse weather (rain) and no incidents for two lanes was 1624 veh/hr/ln. Similarly, the average capacity for three and four lanes was found to be 1693 veh/hr/ln and 1626 veh/hr/ln, respectively.

5.1.4. Capacity for Adverse Weather (Rain) and Incidents

The average discharge flow was used to identify the capacity during incidents and rain. Furthermore, the average discharge flow per open lane is shown in Tables 23 through 31. Finally, t-tests were carried out to compare average discharge flow during incidents measured upstream or within the closure for two, three, and four lanes.

- **Two-Lanes Capacity for Rain and Incidents Measured Upstream of Lane Closure**

As shown in Table 24, ten observations were found in this category of incidents measured upstream of closure during rain. The average discharge flow (i.e., capacity) was 2,114 veh/hr. The average per lane capacity was 1,057 veh/hr/ln.

Table 24 Rain and Incidents Capacity for Two-Lane (Measured Upstream of Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-35 S @ 159TH STREET	2	2292	2	1146
US-69 N @ 135TH STREET	2	2016	2	1008
I-70 E @ I-435	2	2220	2	1110
I-470 N @ NORTH OF LAKEWOOD	2	1572	2	786
K-10 W @ RIDGEVIEW	2	1452	2	726
I-70 W @ ADMIRAL BLVD	2	2484	2	1242
US-69 N @ COLLEGE	2	1872	2	936
K-10 W @ AT RENNER ROAD	2	2688	2	1344
I-35 N @ 167TH STREET	2	2328	2	1164
K-10 E @ WEST OF RIDGEVIEW	2	2220	2	1110
Average		2114		1057
Standard Deviation		390		195

- **Two-Lanes Rain and Incidents Measured Within Lane Closure**

Only six events were collected for the two-lanes with incidents during rain measured within the lane closure (Table 25). The average discharge flow was 1,436 veh/hr. The average discharge flow per remaining lanes (i.e., one lane) was 1,436 veh/hr/ln.

Table 25 Rain and Incidents Capacity for Two-Lane (One Lane Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-470 S @ I-70	2	1176	1	1176
K-10 E @ WEST OF RENNER RD	2	1488	1	1488
I-70 E @ I-MILL ST	2	1176	1	1176
I-35 S @ 159TH STREET	2	1620	1	1620
K-10 W @ WEST OF RIDGEVIEW	2	1536	1	1536
I-35 S @ 159TH STREET	2	1620	1	1620
Average		1436		1436
Standard Deviation		208		208

T-tests were applied to identify whether the difference between the two measurement locations during incidents and rain was statistically significant. According to Table 26, the resulting p-value equals 0.0025, which is much less than 0.025. Thus, the difference is considered to be statistically significant.

Table 26 Two-Lanes T-Statistic Between Incidents during Rain Measured Upstream and Within the Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1057	1436
N	10	6
Std. Deviation	195	208
Std. Error Mean	62	85

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Incidents upstream closure-incidents within closure	14	3.6744	0.0025

The two-tailed p-value indicated that the impact of measurement location on the capacities of segments during incidents and rainy conditions is significant.

- **Three-Lanes Rain and Incidents Measured Upstream of Lane Closure**

Table 27 shows the observed three-lanes incidents capacity obtained during rain from eleven locations. Several detectors located along I-70 Eastbound and Westbound and I-435 Northbound, Southbound, and Westbound were used to obtain the data. The average discharge flow was 3,142 veh/hr, and the average capacity per open lane was 1,047 veh/hr/ln.

Table 27 Rain and Incidents Capacity for Three-Lane (Upstream of Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-70 E @ 31ST ST	3	3636	3	1212
I-70 E @ East of Chrysler Ave	3	3600	3	1200
I-70 W @ 23RD ST	3	4008	3	1336
I-70 E @ LISTER AVE	3	3156	3	1052
I-435 N @ South of Winner Rd	3	2760	3	920
I-70 E @ LISTER AVE	3	2748	3	916
I-435 S @ 79TH STREET	3	3096	3	1032
I-435 S @ STADIUM DRIVE	3	2736	3	912
I-435 W @ GREGORY BLVD	3	2952	3	984
I-70 W @ I-470 INTERCHANGE	3	3000	3	1000
I-435 N @ 23RD STREET	3	2868	3	956
Average		3142		1047
Standard Deviation		425		142

- **Three-Lanes Rain and Incidents Measured Within Lane Closure**

The observed discharge flow during incidents and rain for three-lane freeways are shown in Table 28. The traffic data were retrieved from the detectors located on I-35, I-470, I-70, I-635, and I-670. The average capacity was 3,084 veh/hr. Also, the average capacity per open lane was found to be 1,235 veh/hr/ln.

Table 28 Rain and Incidents Capacity for Three-Lane (Within Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-35 N @ NORTH OF MILL ST	3	3372	2	1686
I-470 E @ VIEW HIGH ROAD	3	2592	2	1296
I-70 W @ 23RD ST	3	2280	2	1140
I-35 N @ 75TH ST	3	2304	2	1152
I-435 S @ SOUTH OF 210 HIGHWAY	3	3396	2	1698
I-435 S @ PARVIN ROAD	3	2352	2	1176
I-435 E @ AT 350 HWY	3	2676	2	1338
I-635 S @ NORTH OF MERRIAM	2	2052	2	1026
I-70 E @ 27TH ST	3	2028	2	1014
I-635 N @ DOUGLAS AVE	3	1956	2	978
I-435 E @ NORTH OF 83RD ST	3	2136	2	1068
I-70 W @ 23RD ST	3	1920	2	960
I-35 S @ PRAIRE STREET	3	2280	2	1140
I-435 S @ PARVIN ROAD	3	2628	2	1314
I-670 W @ PAST CHARLOTTE	3	3084	2	1542
Average		2470		1235
Standard Deviation		485		242

Table 29 shows the results from the t-test. Using a 95% confidence interval, the resulting two-tailed p-value indicated a significant difference between capacities during incidents and rain measured upstream and within the closure.

Table 29 Three-Lanes T-Statistic Between Incidents during Rain Upstream and Within Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1047	1235
N	11	15
Std. Deviation	142	242
Std. Error Mean	43	62

	Degree of Freedom	T-score	P value (2-tailed)
Incidents upstream closure-incidents within closure	24	2.2956	0.0307

As the difference between incident capacities measured upstream and within the closure is considered to be statistically significant, the null hypothesis is rejected. Thus, the effect of incidents by measurement location is meaningful, and the results from Table 27 and Table 28 are different.

- ## Four-Lanes Rain and Incidents Measured Upstream of Lane Closure

The twelve detectors, shown in Table 30 and located on I-35, I-435, and I-635, collected the traffic data for incidents during rain measured upstream of a lane closure. The average capacity was 4,702 veh/hr. Also, the average per open lane capacity was 1,176 veh/hr/ln.

Table 30 Rain and Incidents Capacity for Four-Lane (Upstream of Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-35 S @ JOHNSON DR	4	5292	4	1323
I-435 E @ AT 104TH ST	4	5064	4	1266
I-35 S @ ANTIOCH RD	4	4320	4	1080
I-35 S @ West Pennway	4	4368	4	1092
I-635 S @ High Drive	4	3960	4	990
I-35 S @ ANTIOCH RD	4	4380	4	1095
I-35 S @ North of ANTIOCH RD	4	4200	4	1050
I-35 S @ ANTIOCH RD	4	3576	4	894
I-35 N @ West Pennway	4	4788	4	1197
I-435 W @ AT 104TH ST	4	5520	4	1380
I-35 N @ ANTIOCH RD	4	5748	4	1437
I-35 S @ 67TH ST	4	5208	4	1302
Average		4702		1176
Standard Deviation		670		167

- **Four-Lanes Rain and Incidents Measured Within Lane Closure**

Average discharge flow at four-lane segments with incidents during rain measured within the lane closure, are presented in Table 31. The average discharge flow (i.e., capacity) was 3,446 veh/hr. The average capacity per open lane was 1,149 veh/hr/ln.

Table 31 Rain and Incidents Capacity for Four-Lane (Within Closure)

Detector	Number of Lanes	Discharge Flow (veh/hr)	Number of Open Lanes	Discharge Flow per open lane (veh/hr/ln)
I-35 S @ 75TH ST	4	3612	3	1204
I-470 W @ BLUE RIDGE BLVD	4	3252	3	1084
I-635 S @ NORTH OF MERRIAM	4	3168	3	1056
I-35 S @ ANTIOCH RD	4	4788	3	1596
I-435 E @ EAST OF HWY 69	4	3348	3	1116
I-435 E @ INDIAN CREEK	4	3456	3	1152
I-435 E @ STATE LINE RD	4	3288	3	1096
I-35 S @ ANTIOCH RD	4	2700	3	900
I-70 E @ 18TH STREET	4	3060	3	1020
I-470 W @ BLUE RIDGE BLVD	4	3192	3	1064
I-70 W @ I-470	4	3480	3	1160
I-35 S @ 63RD ST / SHAWNEE MI	4	4008	3	1336
I-35 S @ NORTH OF ANTIOCH RD	4	2868	3	956
I-35 N @ WEST PENNWAY	4	3600	3	1200
I-35 N @ 67TH ST	4	3864	3	1288
Average		3446		1149
Standard Deviation		507		169

T-test was carried out to measure the difference between rain and incidents, as shown in Table 32. The resultant two-tailed p-value equals 0.6819, which is greater than 0.05. Thus, there is no statistical difference between the two capacities.

Table 32 Four-Lanes T-Statistic Between Incidents during Rain Measured Upstream and Within the Lane Closure

Capacity		
Category	**Incidents Measured Upstream of Closure**	**Incidents Measured Within Closure**
Mean	1176	1149
N	12	15
Std. Deviation	167	169
Std. Error Mean	48	44

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Incidents upstream closure-incidents within closure	25	0.4147	0.6819

The two-tailed p-value indicated that there was no difference between the results from Table 30 and Table 31. As a result, a new table (Table 33) was developed to combine the observations in terms of four-lanes incidents during rain. The average per lane discharge flow for the combined data was 1,161 veh/hr/ln.

Table 33 Four-Lanes Incidents and Rain Capacity

Detector	Number of Lanes	Discharge Flow per open lane (veh/hr/ln)
I-35 S @ JOHNSON DR	4	1323
I-435 E @ AT 104TH ST	4	1266
I-35 S @ ANTIOCH RD	4	1080
I-35 S @ WEST PENNWAY	4	1092
I-635 S @ HIGH DRIVE	4	990
I-35 S @ ANTIOCH RD	4	1095
I-35 S @ NORTH OF ANTIOCH RD	4	1050
I-35 S @ ANTIOCH RD	4	894
I-35 N @ WEST PENNWAY	4	1197
I-435 W @ AT 104TH ST	4	1380
I-35 N @ ANTIOCH RD	4	1437
I-35 S @ 67TH ST	4	1302
I-35 S @ 75TH ST	4	1204
I-470 W @ BLUE RIDGE BLVD	4	1084

I-635 S @ NORTH OF MERRIAM	4	1056
I-35 S @ ANTIOCH RD	4	1596
I-435 E @ EAST OF HWY 69	4	1116
I-435 E @ INDIAN CREEK	4	1152
I-435 E @ STATE LINE RD	4	1096
I-35 S @ ANTIOCH RD	4	900
I-70 E @ 18TH STREET	4	1020
I-470 W @ BLUE RIDGE BLVD	4	1064
I-70 W @ I-470	4	1160
I-35 S @ 63RD ST / SHAWNEE MI	4	1336
I-35 S @ NORTH OF ANTIOCH RD	4	956
I-35 N @ WEST PENNWAY	4	1200
I-35 N @ 67TH ST	4	1288
Average		1161
Standard Deviation		166

In summary, the measurement location resulted in significant differences for the two-lane and three-lane freeways, but not for the four-lane freeways.

5.2. Free-Flow Speed Results

The average free-flow speed was observed from the same locations used previously for the capacity measurements. The results are listed in Table 34 as follows.

1- FFS for base conditions
2- FFS during incidents (good weather)
3- FFS during adverse weather (rain and no incidents)
4- FFS for adverse weather (Rain), and incidents

Two sample t-tests were carried out to investigate the difference in the FFS between incidents measured upstream of the closure and within the closure at the study locations. The measurement location was not found to affect FFS during incidents, or incidents with rain, irrespective of the number of lanes. As a result, incidents measured upstream and within the closure were combined in Table 34. For example, the average three-lanes FFS during incidents was 62 mph. Similarly, the average FFS for four-lane freeways during rain and incidents was 53 mph.

Table 34 Observed Free-Flow Speed

	FFS (mph)	St. Dev (mph)	Number of Observations
Base Conditions			
2-lanes	68.2	5.3	29
3-lanes	65.1	4.2	47
4-lanes	62.6	2.7	22
Incidents			
2-lanes	61.6	7.6	17
3-lanes	61.9	5.5	43
4-lanes	58.9	4.8	38
Adverse Weather (rain)			
2-lanes	67.8	2.5	13
3-lanes	61.5	4.6	20
4-lanes	63.8	4.1	16
Adverse Weather (Rain) and Incidents			
2-lanes	62.5	6.7	14
3-lanes	60.9	5.6	25
4-lanes	52.9	5.2	26

5.3. Statistical Analysis for Capacity

In order to obtain CAF, the average capacities for the base conditions were compared to the capacities for the remaining conditions. The statistical difference between those capacities was investigated first using a 2-tailed t-test, with 95% confidence intervals. The events were divided into two groups: non-incident scenarios, and incident scenarios. After that, final tables for CAF were presented as a function of adverse weather and no incidents for the no-incident conditions, and as a function of the number of lanes as well as measurement locations for incident conditions.

5.3.1. Effect of Adverse Weather on Capacity

The observed average breakdown flow rates (i.e., capacity) were compared with the base conditions and the adverse weather (rain) and no incident conditions. The following tables show the results of the t-test analysis.

- **Two-lanes**

The t-test results are shown in Table 35. With a 95% confidence interval, the two-tailed p-value of 0.7360 is greater than 0.025, which indicated that the difference is considered to be not statistically significant, thus failing to reject the null hypothesis. This means that rain does not impact capacity at two-lane segments.

Table 35 T-Statistic for Two-Lane During Non-Incidents Conditions

Capacity		
Category	**Base Conditions**	**Rain**
Mean	1645	1624
N	29	13
Std. Deviation	163	229
Std. Error Mean	30.27	63.51

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions-Rain	40	0.3396	0.7360

- **Three-Lanes**

The results shown in Table *36* indicated that the difference between the average capacity during base conditions and during rain is considered to be not significant, so the null hypothesis is not rejected. The two-tailed p-value equals 0.2789, which is higher than 0.025. As such, rain does not affect capacity of three-lane freeways.

Table 36 T-Statistic for Three-Lane During Non-Incidents Conditions

Capacity		
Category	**Base Conditions**	**Rain**
Mean	1746	1693
N	47	20
Std. Deviation	177	193
Std. Error Mean	25.82	43.16

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions-Rain	65	1.0918	0.2789

- ## Four-Lane

The results shown in Table 37 indicate that the difference between base and rain conditions is not significant at four-lane segments. The two-tailed p-value equals 0.8962 which is greater than 0.025. As a result, the null hypothesis could not be rejected.

Table 37 T-Statistic for Four-Lane During Non-Incidents Conditions

Capacity		
Category	**Base Conditions**	**Rain**
Mean	1633	1626
N	22	16
Std. Deviation	160	165
Std. Error Mean	34.11	41.25

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions-Rain	36	0.1314	0.8962

In summary, rain did not result in statistically significant capacity differences in two-, three-, or four-lane segments; therefore, CAFs cannot be estimated based on the data analyzed in this research.

5.3.2. Effect of Incidents on Capacity

As a function of the number of lanes, as well as measurement location, a two-tailed t-test was carried out to identify the significance level between the different incident's conditions. The average base capacity was compared to the average incidents during good weather and then compared to rain with incident conditions. As it was discussed earlier, the average breakdown flow was used to measure the base capacity, while the average discharge flow was used to measure the incidents capacity. However, to analyze the base conditions and incidents conditions accurate, the average discharge flow observed during base conditions was compared to the average discharge flow for incident conditions. Also, the average discharge flow during the base conditions for two-, three- and four-lane freeways was found to be 1570 veh/hr/ln, 1577 veh/hr/ln and 1517, respectively. The measurement location during good weather incidents was not considered for two, three, and four lanes as the statistical analysis showed no significant differences. On the other hand, the effect of measurement location for incidents and rain conditions was considered for two- and three-lane segments, while it was not measured for four-lane segments.

- **Incident Capacity for Two-Lanes**

Table 38 shows the average discharge flow for four different conditions, and the resulting t-test. The Capacity for base conditions was found to be significantly different compared to the capacities during incidents (and good weather), rain and incidents (measured upstream of closure), and rain and incidents (measured within the closure).

Table 38 T-Statistic for Two-Lane Incidents Capacity

Capacity				
Category	**Base Conditions**	**Incidents (Good Weather)**	**Rain and incidents (upstream of closure)**	**Rain and Incidents (within closure)**
Mean	1570	1102	1057	1436
N	29	18	10	6
Std. Deviation	108	244	195	208
Std. Error Mean	20	58	62	85

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions- Incidents (Good Weather)	45	9.0427	0.000

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions- Rain and Incidents (upstream of closure)	37	10.4047	0.000

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions - Rain and Incidents (within closure)	33	2.3294	0.013

In summary, the statistical analysis indicated that incidents during good weather and incidents during rain, measured upstream or within the lane closure, had an effect on capacity for two-lane freeways.

- ### Incident Capacity for Three-Lanes

In this section, the average discharge flow from the base conditions was compared to the average discharge flow from the incidents during good weather conditions. Also, incidents and rain by measurement location were considered in three lanes capacity, while the average of base conditions was compared twice, both to incidents measured upstream of closure and incidents measured within the closure, as seen in Table 39. The results from the t-test indicated significant difference among the four conditions.

Table 39 T-Statistic for Three-Lane Incidents Capacity

Capacity				
Category	**Base Conditions**	**Incidents (Good Weather)**	**Rain and incidents (Upstream of Closure)**	**Rain and Incidents (Within Closure)**
Mean	1577	1304	1047	1235
N	47	44	11	15
Std. Deviation	168	231	142	242
Std. Error Mean	25	35	43	63

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions- Incidents (Good Weather)	89	6.4773	0.000

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions- Rain and Incidents (upstream of closure)	56	9.6686	0.000

	Degree of Freedom	T-score	P value (2-tailed)
Base Conditions - Rain and Incidents (within closure)	60	6.1379	0.000

The t-test analysis asserted the effect of incidents on three-lanes capacity. Incidents during base weather, as well as incidents during rain, had an impact on the capacity at three lane freeways.

- ## Incident Capacity for Four-lanes

Unlike two- and three-lane freeways, the measurement location was not found to affect capacity during rain and incidents at four-lane freeways. Additionally, the measurement location did not affect the good weather incidents capacity at four-lane freeways. Thus, average discharge flow from the base condition was compared to incidents capacity, as well as the capacity under rain and incidents conditions, without taking into account the measurement location (Table 40).

The results indicated a significant difference between the capacities as the resulting p-value was less than 0.0001. Also, the comparison between the base condition and rain with incidents resulted in a p-value of less than 0.025.

Table 40 T-Statistic for Four-Lane Incidents

Capacity			
Category	**Base Conditions**	**Good Weather (with Incidents)**	**Rain and Incidents**
Mean	1517	1257	1161
N	22	39	27
Std. Deviation	127	157	166
Std. Error Mean	27	25	32

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Incidents (Good Weather)	59	6.6322	0.000

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Rain and Incidents	47	8.2724	0.000

According to the statistical analysis results shown in Table 38, Table 39, and Table 40, an effect of incidents on capacity was found. Good weather incidents had an impact on the capacity of two, three, and four lanes. Also, rain and incidents at two- and three-lane freeways, affected the capacity. Likewise, incidents, as well as incidents and rain had an impact on four-lane capacity.

5.4. Statistical Analysis for Free-Flow Speed

This part provides the results of the statistical analysis for FFS. T-tests were carried out to examine the effect of rain (no incidents) and incidents conditions on Free-Flow Speed.

5.4.1. Effect of Adverse Weather on Free-Flow Speed

In this section, the observed Free-Flow Speed during base conditions was compared to the Free-Flow Speed during rain without any incidents. T-test was used to assess the difference between the two conditions, and a 95% significance level was used throughout the statistical analysis.

- **Two-Lanes**

Table 41 shows the results of the statistical analysis. The two-tailed p-value is equal to 0.7976, which indicated no difference in FFS between base conditions and rain without any incidents.

Table 41 T-Statistic for Two-Lane During Adverse Weather (Rain)

FFS		
Category	**Base Conditions**	**Rain**
Mean	68.2	67.8
N	29	13
Std. Deviation	5.3	2.5
Std. Error Mean	0.98	0.693

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions-Rain	40	0.2582	0.7976

- **Three-Lanes**

The resultant two-tailed p-value equaling 0.0027 indicated that the difference is considered to be statistically significant, at $p<0.05$, between the base conditions and rain without incidents at the three-lane freeways, as demonstrated in Table 42.

Table 42 T-Statistic for Three-Lane During Adverse Weather (Rain)

FFS		
Category	**Base Conditions**	**Rain**
Mean	65.1	61.5
N	47	20
Std. Deviation	4.2	4.6
Std. Error Mean	0.613	1.03

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions-Rain	65	3.1208	0.0027

- **Four-Lanes**

Table 43 shows the t-test results of average FFS during the base conditions and the average FFS during rain without incident conditions. The observed p-value equals 0.2863 which is greater than 0.025. As a result, the difference in this case is considered to be not statistically significant.

Table 43 T-Statistic for Four-Lane During Adverse Weather (Rain)

FFS		
Category	**Base Conditions**	**Rain**
Mean	62.6	63.8
N	22	16
Std. Deviation	2.7	4.1
Std. Error Mean	0.58	1.025

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions-Rain	36	1.0886	0.2863

The statistical analysis of this section demonstrated that only Free-Flow Speed on the three-lanes facility was affected by adverse weather (rain) conditions. Nevertheless, adverse weather did not have an impact on Free-Flow Speed on two and four lanes freeways.

5.4.2. Effect of Incident on Free-Flow Speed

Incidents Free-Flow Speed was observed during rain, as well as during good weather conditions. As discussed previously, the difference between FFS during Incidents measured upstream of a lane closure and FFS during Incidents measured within the Lane Closure were statistically insignificant for two-, three-, and four-lane freeways. Thus, incidents by measurement location were not considered for this analysis. In this section, T-test was carried out, with a confidence interval of 95%, between the average FFS during Base Conditions and Incidents FFS during Good Weather conditions. Similarly, FFS during incidents and rain was compared to FFS during base conditions.

- **Incidents Free-Flow Speed at Two-Lanes**

As indicated in Table 44, the difference between the average FFS from the Base Conditions and Incidents with Good Weather resulted in a two-tailed p-value of 0.0012, which is less than 0.025. This finding indicated that the difference is considered to be statistically significant at $p<0.05$. Thus, the null hypothesis was rejected. Furthermore, the relationship between FFS during base conditions and FFS during rain and incidents reflected a statistical significance. The pulled p-value from the two-tailed t-test was found to be 0.0042, which is less than 0.025.

Table 44 T-Statistics for Two-Lane Incident FFS

Two-Lanes FFS			
Category	**Base Conditions**	**Good Weather (Incidents)**	**Rain and Incidents**
Mean	68.2	61.6	62.5
N	29	17	14
Std. Deviation	5.3	7.6	6.7
Std. Error Mean	0.98	1.84	1.8

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Incidents (Good Weather)	44	3.4652	0.0012

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Rain and Incidents	41	3.0298	0.0042

Based on the results shown in Table 44, incidents affected FFS on two-lanes. The t-test indicated that FFS was impacted by incidents during good weather on two-lane freeways. Incidents and rain also influenced FFS on two-lane freeways.

- **Incidents Free-Flow Speed at Three-Lanes**

The difference between the conditions presented in Table 45 was found to be significant. The p-value from the relationship between base conditions and incidents during Good Weather was 0.0025, which is less than 0.025. Likewise, the two-tailed p-value from the difference between the base conditions and incidents during rain was 0.0006, which indicates a significant difference between them.

Table 45 T-Statistics for Three-Lane Incident FFS

Three-Lanes FFS			
Category	**Base Conditions**	**Good Weather (Incidents)**	**Rain and Incidents**
Mean	65.1	61.9	60.9
N	47	43	25
Std. Deviation	4.2	5.5	5.6
Std. Error Mean	0.61	0.839	1.12

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Incidents (Good Weather)	88	3.1176	0.0025

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Rain and Incidents	70	3.5894	0.0006

Finally, the above results demonstrated the effect of incidents on FFS at three-lane freeways. Incidents during good weather, as well as incidents during rain affected FFS at three-lane segments.

- **Incidents Free-Flow Speed at Four-Lanes**

T-test was used to compare the average FFS during different conditions at four-lane freeways. The outcomes specified that the differences are considered statistically significant between all the conditions that were compared (Table 46).

Table 46 T-Statistic for Four-Lane Incidents FFS

Four-Lanes FFS			
Category	**Base Conditions**	**Good Weather (Incidents)**	**Rain and Incidents**
Mean	62.6	58.9	52.9
N	22	38	26
Std. Deviation	2.7	4.8	5.2
Std. Error Mean	0.576	0.779	1.02

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Incidents (Good Weather)	58	3.3169	0.0016

	Degree of Freedom	**T-score**	**P value (2-tailed)**
Base Conditions- Rain and Incidents	46	7.8873	0.0001

The effect of incidents on FFS was meaningful for four-lane freeways. Good weather incidents, as well as incidents during rain according to the statistical analysis shown in Table 46, affected the FFS on four-lane freeways.

5.4.3. Conclusions

The process of obtaining capacity and FFS involved comparing the average capacity as well as FFS during base conditions to the remaining conditions that included incidents, rain without incidents, and incidents during rain. It was essential to statistically examine the differences between those conditions before developing the CAFs and SAFs. Thus, t-tests were carried out and the results were as follows.

1- Capacity:

Comparison between capacity under base conditions and capacity under adverse weather showed no significant difference, therefore, it can be assumed that rain did not affect capacity at the study locations.

For the effect of incidents on capacity, the statistical analysis showed that incidents affected capacity at all freeway segments. Rain and incidents also affected capacity for all segments studied. Under these conditions, the measurement location was also found to affect capacity at two-lane and three-lane segments.

2- Free-Flow Speed:

Adverse weather (rain) had a negative impact on FFS on three-lane freeways only. Incidents (assuming good weather) as well as incidents under rain also affected FFS for all study segments. The measurement location during incidents was not found to significantly impact FFS.

5.5. Capacity and Free-Flow Speed Adjustment Factors

In this section, the final results of the Capacity Adjustment Factors (CAF) and the Speed Adjustment Factors (SAF) are presented. The results involve the impact of rain, incidents, and incidents with rain conditions.

5.5.1. Capacity Adjustment Factors (CAF) for Adverse Weather (Rain)

The statistical analysis showed no effect of adverse weather (rain) on the capacity for two, three, and four lane segments. Therefore, the remaining capacity (i.e., CAF) due to adverse weather was not quantified in this study.

5.5.2. Capacity Adjustment Factors (CAF) for Incidents and Incidents with Rain

Table 47 shows the final CAFs results. The first three CAFs concern incidents during good weather. For example, the remaining capacity during incidents (and good weather) is 70% of the capacity during base conditions. In addition, the measurement location was considered for incidents and rain conditions for two and three lane segments. For instance, capacity during incidents measured within the lane closure and rain at three-lane freeways was reduced by 22%.

Table 47 Capacity Adjustment Factors (CAF) for Incidents and Incidents with Rain by Number of Lanes

	CAF
Incidents	
Two-Lanes	0.70
Three-Lanes	0.83
Four-Lanes	0.83
Incidents and Rain	
Two-Lanes Upstream of Closure	0.67
Two-Lanes Within Closure	0.91
Three-Lanes Upstream of Closure	0.66
Three-Lanes Within Closure	0.78
Four-Lanes	0.77

5.5.3. Speed Adjustment Factors (SAF) for Adverse Weather

The statistical analysis showed no effect of adverse weather on FFS on two and four lanes freeway, while the impact was only detected on three lanes freeway, as can be seen in Table 48. Adverse weather (rain) reduced FFS on three-lanes facilities by 5%. Thus, the FFS was maintained by 95% during rain.

Table 48 Speed Adjustment Factor (SAF) for Adverse Weather (Rain)

Adverse Weather (Rain)	FFS Adjustment Factors (SAF)
Two-Lane	N/A
Three-Lane	0.95
Four-Lane	N/A

5.5.4. Speed Adjustment Factors (SAF) for Incidents and Incidents with Rain

Table 49 shows the free-flow speed adjustment factors for incidents and good weather, and incidents and rain. For example, the remaining FFS at two-lane segments when incidents occur was 91% of the FFS during base conditions.

Table 49 Speed Adjustment Factors (SAF) for Incidents and Incidents with Rain

	SAF
Incidents	
Two-Lanes	0.90
Three-Lanes	0.95
Four-Lanes	0.94
Incidents and Rain	
Two-Lanes	0.92
Three-Lanes	0.94
Four-Lanes	0.84

6. SUMMARY AND CONCLUSIONS

This section presents a summary of the methods used to obtain the observed capacities and free-flow speeds and adjustment factors. The final results are discussed, and some recommendations are suggested for future studies.

This study focused on estimating the effect of rain and incidents on capacity as well as free-flow speed, using data from Kansas City for the period from 2014 to 2018. KCSCOUT and Weather Underground were the primary resources for the data collection. Four conditions were considered in this thesis: (1) base conditions that did not include incidents or adverse weather, (2) incident conditions during good weather, (3) rain conditions without incidents, and (4) incident conditions during rainy weather. Also, the type of lane closure during incidents was evaluated.

6.1. Conclusions

CAFs and SAFs as the function of weather (no incidents) were calculated by comparing the average from the base conditions to the average from rainy conditions. However, the effect of adverse weather (rain) on capacity was not found to be significant, and only FFS at three-lane segments was impacted by rain. SAF for three-lanes during rain without any incidents was 0.95.

CAFs and SAFs were estimated by comparing the average from the base conditions to the average from incident (during good weather) or incidents during rainy conditions. Overall, incidents, as well as incidents during rain, affected capacity and FFS. Also, the measurement location affected the capacity for incidents during rain at two and three lane segments. Nevertheless, our analysis indicated that incidents by measurement location did not have an impact on good weather incidents at the study locations. The same analysis, also, showed that incidents by measurement location did not have an effect on FFS for two-, three, and four-lanes at the study locations.

CAFs during incidents (and good weather) were 0.70, 0.83 and 0.83 for two, three, and four lane segments, respectively. CAF for incidents and rain (measured upstream of the lane closure) was 0.67, 0.66, and 0.77 at two-lane, three-lane, and four-lane segments respectively. Incidents and rain affected capacity (measured within the closure) on two-lane and three-lane segments, with CAFs equal to 0.91 and 0.78, respectively.

While HCM6 (1) did not study the effect of incidents on FFS, this thesis conducted several SAFs for both incidents and incidents during rain. The remaining FFSs when incidents occurred were 0.90 for two-lanes, 0.95 for three-lanes, and 0.94 for four-lanes. Similarly, two, three, and four lanes were able to handle 92%, 94%, and 84%, respectively, when both rain and incidents occurred.

6.2. Recommendations

This section provides recommendations for future studies.

- The Highway Capacity Manual 6th edition (HCM6) (1), estimated default CAFs as a function of adverse weather (no incidents). However, the results from this thesis indicated no effect of adverse weather on capacity. This may be due to the limited data that were analyzed in this thesis, or the focus on only rain as adverse weather conditions. As such, future studies should focus on analyzing a larger set of data with possibly more adverse weather.
- HCM6 (1) did not study CAFs and SAFs as a function of incidents associated with adverse weather. Their assumption was that incidents and adverse weather are two independent events; therefore, when both happen at the same time the resulting CAF is estimated from the product of the two separate CAFs (1). However, this has not been validated by actual data. Although this research did not find any impact on capacity during adverse weather alone, when incidents occur during rain the capacity drop is more

severe compared to during incidents only. Therefore, the multiplicative effect of rain and incidents as suggested in the HCM6 was not verified in this thesis.

- Data collection on two-lane segments were challenging due to a lack of related events. Therefore, future study might expand the number of observations for two lane freeways by collecting data at different locations outside of Kansas City or the Kansas City metro area. It is also recommended that future research use other data sources such as RITIS or PeMS that provides a wide range of access to other states freeway data macroscopic flow database and incident records.
- Five-lane freeways were initially considered in this thesis. However, limited data were available on five-lane freeways. Thus, future research should expand on five-lane freeways. This could be done by accessing other data source as mentioned in the previous bullet point.
- It is also recommended to examine the effect of incidents with more than one lane blockage, similar to the HCM6.

The limitations of this study are listed as following:

- One of the limitations of this study is the inability to construct the breakdown probability function during incident or rain. The breakdown probability function gives a more precise idea regarding the probability of a breakdown at a certain flow. Breakdown probability function has been investigated in freeway capacity studies, and it is regarded as a major tool to predict freeway capacity.
- This study does not evaluate the impact of incidents on the fundamental diagram. In other words, Flow-Density and Speed-Flow diagram can be generated for adverse weather or incidents.

- This study only focused on events that were caused by vehicle-vehicle crashes. Other events types such as stalled vehicle, debris, emergency vehicles, etc. were excluded during the data collection phase.
- Incident time (e.g. initial response, incident clearance, roadway clearance, and time to return to normal condition) was not considered as a factor while evaluating the freeway capacity or FFS.

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